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UNDERGROUND CORROSION

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PREFACE

Bureau Circular C401, Abstracts and Summaries of Bureau of Standards Publications on Stray-Current Electrolysis, was published in 1933. This gives the essential conclusions drawn from the work of the National Bureau of Standards on stray-current electrolysis during a period of 15 years, as presented in 17 Bureau Technologic Papers, most of which are available only in reference libraries.

As corrosion due to stray-current electrolysis became less important, attention was turned to underground corrosion due to causes other than stray currents. Although this work has been interrupted by the necessity of giving full attention to war work, the subject continues to be one of major importance. A considerable number of Bureau publications have been issued, but most of them are also out of print and available only in reference libraries.

There is a continuing demand for technical information relating to the problem of underground corrosion. Because of the extensive installation and repair of underground structures that will occur in the postwar period the Bureau feels that the issuance of a publication giving under one cover the research results obtained thus far, together with a general discussion of the corrosion problem and the conclusions to be drawn from the data, will serve a useful purpose. These conclusions are supplemented by summaries of the results of the more important investigations of underground-corrosion phenomena carried on in America and Europe.

The manufacturers who supplied the materials tested have rendered valuable assistance in planning the tests and in the interpretation of the results. The cooperation of the public utilities and the technical societies has also been of great value in the work.

The material for this Circular is based on the results obtained by many members of the Bureau's Underground Corrosion Section over a period of several years, and the use of their data is acknowledged by the author.

E. U. Condon, *Director.*

UNDERGROUND CORROSION

By Kirk H. Logan

ABSTRACT

This Circular is an assembly of the results of the National Bureau of Standards investigations of underground corrosion which began in 1922. The fundamental causes and processes of underground corrosion are the same as those occurring in the air or water, but their relative values are different. Corrosion in soils is the result of soil characteristics and conditions but these are too numerous and complex to permit a satisfactory correlation of corrosion with any single soil property.

The results of the tests of ferrous materials given in this Circular indicate that the commonly used ferrous pipe materials do not differ greatly in their resistance to soils and that their apparent relative merits are either accidental or dependent on soil conditions. Low-alloy ferrous materials lose weight more slowly than unalloyed ferrous materials, but are penetrated by corrosion as rapidly. Alloys high in nickel and chromium are very resistant to corrosion.

In most of the soils investigated the rate of corrosion of ferrous materials decreases as the exposure is prolonged. Any rate of corrosion is applicable only to the area of the metal tested and the time it was exposed. The life of a pipe cannot be predicted solely from the loss of weight or the depth of a pit at any given time. The corrosiveness of the soil can be indicated only by a formula which takes account of the characteristics of the soil to which the pipe is exposed, the change in the rate of corrosion with time and the area of the exposed metal.

The data in the Circular show that copper and alloys high in copper corrode much less and more uniformly than ferrous materials. Lead was resistant to many soils but pits deeply in some soils.

The effectiveness of metallic coatings depends on the soils to which they are exposed. No metallic coating is suitable for all soils. Bituminous coatings greatly retard the loss of metal to which they are applied. Their effectiveness is roughly proportional to their thickness. Few coatings are free from all pinholes and other imperfections. Important causes of coating failures are improper application and injuries incidental to pipe laying. Better tools and methods have considerably reduced the number of failures attributable to these causes, but it is still difficult to secure a completely protected pipe and some coatings are injured by soil stress and roots of trees, shrubs, and grass.

The results of tests of a number of promising coatings developed in the laboratory are presented.

Several methods of testing soils and coatings are described and their usefulness discussed. The effectiveness of several methods of preventing corrosion are compared. Cathodic protection can retard or prevent corrosion under most soil conditions. The paper describes methods of applying cathodic protection under several conditions. Details of test methods and apparatus are given in six appendices.

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I. INTRODUCTION

The prevention of damage to underground structures arising from corrosion has long been an engineering problem of major importance. There are in the United States about 500,000 miles of pipe lines used for transporting water, gas, oil, and gasoline. The value of these lines is in the order of 6 billion dollars. Accurate figures for the corrosion losses of these lines are not available.

The average life of steel mains has been taken as 33⅓ years by the Interstate Commerce Commission.[1] On this basis, the annual cost for replacement of pipe lines would be 200 million dollars. Most of the loss is probably due to corrosion.

In 1910 Congress first made funds available for an investigation by the National Bureau of Standards of the causes of stray-current electrolysis and its mitigation. For 11 years the Bureau conducted field and laboratory tests on this subject. The publications dealing with the results of these investigations are out of print, but they are summarized in Circular C401. These investigations indicated that although very serious corrosion resulted from stray currents, similar corrosion occurred under circumstances that precluded stray currents as an explanation. The Bureau, therefore, undertook to determine whether soils caused corrosion of pipe materials, and, finding some corrosive soils, began the study of the relation of the various properties of soils to corrosion and later of methods for reducing corrosion losses. In this work it had the cooperation of a large number of manufacturers of materials used underground and of the users of these materials. These organizations not only furnished materials and labor but took an active part in the formulation of the conclusions, based on the results of the tests. As the work progressed, the results and conclusions were published from time to time in the National Bureau of Standards Journal of Research and in technical and trade journals. Most of these publications are now out of print. Although these are on file in many public, technical, and college libraries, the data are scattered through so many publications that the results of the investigations are not conveniently available. It is desirable therefore to summarize the work on underground corrosion and to present the more important data in one publication.

There are more than 6,000 specimens of pipe materials still buried at the test sites, including some types on which no data have been obtained. There are also a number of corrosion phenomena that should be studied further. However, the work on underground corrosion has been suspended and the staff assigned to more urgent work for the duration of the war. Because of the need for the data already obtained, the results of the studies of underground corrosion are summarized in this Circular.

Although in many cases the data are insufficient to justify positive conclusions, nevertheless, it seems desirable to suggest tentative conclusions, with the idea of stimulating discussion and further research.

[1] Valuation Docket 1203, Interstate Commerce Commission (1937).

To the conclusions resulting from the investigations of the National Bureau of Standards have been added the results of the more important investigations made elsewhere, and a sufficient number of references have been given to enable the reader to familiarize himself with the details of these investigations insofar as they have been published.

II. INVESTIGATIONS OF UNDERGROUND CORROSION

1. IN FOREIGN COUNTRIES

Although the most extensive investigations of underground corrosion appear to have been carried out in the United States, the records show that similar investigations have been undertaken in several other countries.

The Dutch Research Institute for Metals in 1931 set up a Central Corrosion Committee. This committee delegated its work to various subcommittees, which investigated, among other things the following topics: Corrosive effects of soils on pipes, corrosive effect of soils on cable sheaths, and protective coatings for steel construction. The subcommittee for the effect of soil on pipe consisted of 2 representatives of the Central Committee and 12 officials, engineers, and chemists of laboratories and oil distributors. After a study of foreign literature on corrosion, pipe lines were inspected in various parts of Holland, and laboratory studies of soils, soil waters, and pipe materials were made. The committee issued a report [1][2] in 1935. This will be referred to later. A similar subcommittee on coatings issued a report [2] on coatings, and in 1937 a set of specifications [3] for the coating of pipes with asphalt. In addition to the reports of the committee, individual members of the subcommittees have published a number of papers [4, 5] resulting from their researches. Paralleling some of these papers is a series of reports by Wichers [6, 7].

In Australia several organizations have conducted extensive investigations of underground corrosion and protective coatings, as well as of stray-current electrolysis, the results of which were presented in the technical press and at the 1937 and 1943 National Bureau of Standards Corrosion Conferences [8 to 15]. Most of the conference papers have not been published.

In England the Institution of Civil Engineers, the Iron and Steel Institute, and the British Nonferrous Metals Association organized a Subcommittee on Soil Corrosion of Metals, which, after an investigation and some preliminary experiments, issued an interim report [16] in 1942. A detailed study of anaerobic corrosion [17] has been undertaken in England also. The Post Office Engineering Department [18] has made studies of the corrosion of lead cable sheath and has developed special apparatus for this work. The British Board of Trade [19], after an investigation of stray-current electrolysis, issued a set of regulations to govern tramway installations in 1912, and these have been revised from time to time. The Chemical Research Laboratory of the Department of Scientific and Industrial Research, Teddington, and the Metallurgical Laboratories of Cambridge University have conducted very extensive investigations of corrosion processes of metals and alloys exposed to a large variety of gases and solutions and have done much to establish the electrolytic theory of corrosion. The results of these investigations have been summarized by Evans [20].

[2] Figures in brackets indicate the literature references at the end of this paper.

The study of corrosion has been very extensive in Germany. Stray-current electrolysis has been regulated since 1910. The potential gradient in the rails and the earth were limited and pipe drainage was prohibited. In 1929 the first volume of what was to be a set of books on corrosion [21] was published. This book contained 53 pages of references to articles on corrosion and related subjects, most of which were published in Germany.

Corrosion, especially stray-current electrolysis, has been studied extensively in Japan. An engineer from the Research Department of the Japanese Railways spent a month at the National Bureau of Standards in 1932 studying corrosion literature and methods of testing, and later visited many of the laboratories studying corrosion. Japan contributed four papers to the 1937 Underground Corrosion Conference and was represented at the conference by three engineers.

Severe corrosion of water mains in Winnipeg, Manitoba, led to an extended study of corrosion at the University of Manitoba in Canada [22 to 27], which added considerable information on the corrosion of cast iron.

2. IN THE UNITED STATES

In the United States, underground corrosion has been recognized as a serious problem for many years, and most of the larger companies operating pipe lines employ from one to a dozen or more men whose chief duty is to reduce pipe-line corrosion. One large gas company collected a sample of soil at each point where one of its pipes was exposed until soil conditions through its territory were determined. The data have not been published, but several papers based on them have appeared. Another large gas company has made a statistical study of the service pipe that it has installed at various times. Many pipe-line operators have experimented extensively in the laboratory and in the field with a large variety of protective coatings. From these activities a large quantity of data has accumulated which as yet has not been adequately studied, although many papers based on the data have been published. In many cases definite conclusions cannot be drawn from the corrosion records because the conditions under which the corrosion occurred are not described in sufficient detail. This is especially true with respect to soil conditions.

In 1928 or 1929 the American Gas Association and the American Petroleum Institute each formed a committee on corrosion and employed Research Associates to work at and under the direction of the National Bureau of Standards. For many years thereafter the annual proceedings of these associations contained articles on corrosion by these men and other members of the Associations. Many additional articles on corrosion appeared in technical and trade journals during this period.

One of the most extensive and long-continued studies of corrosion is the investigation by the National Bureau of Standards previously referred to. The data from this investigation have been widely quoted and many conclusions have been drawn therefrom. It should be borne in mind, however, that the tests were planned with definite objectives in view and that, although the data were satisfactory from the point of view of these objectives, it will be necessary to guard against attempting to draw more far-reaching conclusions from them than are justified by the conditions under which the tests were made. In view of the widespread use of the National Bureau of Standards

corrosion data, the tests will be described and the interpretation of the results discussed in considerable detail.

The seriousness of underground corrosion was recognized by Congress in 1910, when the National Bureau of Standards was authorized to make a study of electrolysis caused by stray electric currents and possible methods of its mitigation. The work was carried on actively during a period of 10 years, and the results are reported in 17 Technologic Papers of the National Bureau of Standards. These papers discuss various phases of electrolysis, including surveys, track leakage, electrolysis in concrete, protective coatings, and the design of return feeder systems for street railways. Practically all these papers are now out of print and available only in reference libraries, but abstracts of the papers were published in 1933.

The work of the National Bureau of Standards on corrosion due to causes other than stray currents was started in 1922 and was actively carried on until interrupted by the necessity of giving full attention to war work. In this work, the Bureau has had the support and cooperation of a large number of makers and users of underground pipe and pipe coatings.[3] These organizations have borne much of the expense of the investigations, and their technical representatives have had an active part in planning the tests and in formulating conclusions therefrom.

The results of these investigations, including studies of special phases of underground corrosion carried out by Research Associates working under the direction of the Bureau, have appeared in publications of the Bureau and in publications of the organizations supporting the research projects. In addition, a large number of papers by members of the Bureau staff have been presented before technical societies and published in technical journals.

There are so many diverse factors that affect the corrosion of pipes and other structures underground that the planning of adequate tests and the proper interpretation of the results are matters of considerable difficulty. It is not surprising, therefore, that even experienced corrosion engineers often interpret the same experimental data in different ways. For this reason, it is necessary to guard against the acceptance of too far-reaching or erroneous conclusions, which may be based upon insufficient data or which may be due to failure to take into consideration all the pertinent facts. Unfortunately, it is necessary also to warn against taking at face value the statements contained in publications obviously prepared for the purpose of promoting the sale of some particular product. On the other hand, it is necessary to make as much use as possible of the limited data because the cost of tests sufficiently extensive to warrant definite conclusions on a statistical basis would be prohibitive, even if such tests were feasible. In evaluating the conclusions presented in various publications, therefore, it is always well to take into consideration the experience and standing of their authors.

III. CAUSES OF UNDERGROUND CORROSION

1. GENERAL THEORY

Although the theory of corrosion in general is fairly simple and easily understood, the relative importance of the factors that affect corrosion underground is so difficult to evaluate and the conditions under which corrosion occurs are so poorly defined that the theory is often more help-

[3] A list of the cooperating organizations is given in the Appendix 1.

ful in explaining corrosion that has already taken place than it is in predicting what may be expected. Nevertheless, it is essential as a guide in studying corrosion phenomena and in interpreting the experimental results.

Speller [28] in his book on corrosion gives an easily understood discussion of the electrolytic theory of corrosion. Ewing [29] in a handbook prepared for the American Gas Association, gives an abstract of Speller's discussion. Many phases of corrosion, both from the theoretical point of view and from the practical standpoint, are discussed by Burns and Schuh [30], Hoar [31], and Evans [20]. An extensive discussion of the origin of potential differences leading to corrosion is given by Gatty and Spooner [32]. The following summary of these references, although necessarily too brief to constitute a comprehensive treatment of the theory and phenomena of corrosion, may serve as a guide to the interpretation of the results of the investigations and tests given in this Circular and suggest ways in which corrosion may be at least partially prevented.

Most metals when exposed to air quickly become covered with a film of oxide, which tends to render them more noble, or electropositive, and less corrodible. Unfortunately, this oxide film is often either discontinuous or unstable. If the film-coated metal is in contact with an electrolyte, such as moisture condensed from the atmosphere or with water from some other source, metal particles bearing electric charges (cations) leave the surface of the metal at points where the film is discontinuous (anodes). The simultaneous emission of an equivalent number of electrons from the oxidized surface (cathode) results in the formation of hydroxyl ions, with consequent removal of hydrogen. This migration of ions constitutes a flow of current. The reactions which follow depend on the availability of oxygen and the chemical composition of the electrolyte. The reactions at the anodic and cathodic areas tend to change the potentials of the respective surfaces in opposite directions, thus causing the potential difference to decrease. The potential of the metal with respect to the adjacent electrolyte is a measure of its tendency to discharge ions, that is, to corrode, but this potential does not determine the rate of corrosion. The increase of the potential at the anode because of the accumulation of metal ions in solution and the decrease of the potential of the cathode by the deposit of hydrogen or other processes are known as anodic and cathodic polarization, respectively. It is this polarization of the electrodes that controls the rate of corrosion rather than the potentials recorded in the electromotive series.

Attention is called to the fact that the explanation of corrosion processes began with the assumption of an oxidized and an oxygen-free area on the surface of the metal, the oxidized surface being the one that did not corrode further and was at the higher, or more noble, potential. If this is true, it should be expected that if oxygen can reach some part of a metal surface and thus maintain the oxide film, the part of the surface less subject to oxidation will be anodic to the oxidized surface. This relation between well- and poorly-aerated surfaces has been demonstrated in the laboratory and is the cause of many cases of corrosion, especially in soils. Differences of potential may also occur when two metals are in contact, when the structure of the metal is not uniform because of strains or segregations of impurities, or when the metal contains two distinct materials, such as graphite and ferrite in cast iron. These conditions may be regarded as special cases of points on the

metallic surface that differ in solubility, solution pressure, or electric potential, which terms are different ways of expressing the same phenomenon. Similar conditions occur when the electrolyte in contact with different parts of the metal differs in density or composition.

In the papers referred to [30, 31, 32] the authors have discussed in detail corrosion processes resulting from the exposure of a wide variety of metals and alloys to a large number of solutions.

Corrosion processes in soils are fundamentally the same as in other environments, but the study of underground corrosion is more difficult because the exact soil environment cannot be determined readily, and in many cases this environment is neither uniform nor stable. In brief, the corrosion process is as follows: The positive ions, which travel toward the cathode, may be discharged there. Frequently, however, they lose their charges en route. Under such conditions hydrogen ions are discharged at the cathode. The hydrogen ions may reduce some of the oxide film on the cathode or combine with oxygen in the electrolyte to form hydroxyl ions (alkali) or water or be deposited on the cathode as molecular hydrogen. The collection of alkali or hydrogen at the cathode makes the cathode more noble and reduces the corrosion current. This is one form of cathodic polarization. If ferrous ions leaving the anode contact OH ions in the solution, ferrous hydroxide is formed. Reaction with oxygen results in the formation of ferrous or ferric oxide (rust). If the rust is formed at the anode, it may reduce the rate of corrosion. If the combination occurs at a point remote from the anode, more ferrous ions enter the solution, that is, corrosion continues. Because of the many factors that influence corrosion in soils, it is usually impossible to predict accurately the performance of buried metal or to explain the cause of underground corrosion with assurance. However, although there is necessarily some uncertainty regarding specific cases of corrosion of buried metal, the results of a large number of tests and of observations of corroding pipe lines and other structures have made possible the prediction of the average performance of materials under specified conditions. A large amount of data on underground corrosion has been assembled, which, when generally understood, should aid materially in considering ways and means of reducing losses due to corrosion.

2. SPECIFIC CAUSES

The more important specific causes of underground corrosion may be listed in the order of their relative importance as follows:

Differential aeration.
Acids and salts in the soil.
Differences in characteristics of the soil at different points of contact.
Foreign materials, such as cinders, scraps of metal, or organic materials.
Stray currents (in a few localities).
Nonuniformities in structure or conditions of the metal.
Use of material unsuitable for a given environment.
Interconnection of dissimilar metals.
Anaerobic bacteria.
Long-line currents.

Differential aeration generally results from unequal compactness of the backfill surrounding the buried metal, unequal porosity of the soil at different points, uneven distribution of moisture, and the restriction of the movement of air and moisture in the soil by buildings, roadways,

pavements, and vegetation. Acids and salts in the soil affect the tendency of metals to go into solution. Any differences in the characteristics of the soil in contact with points on the surface of the metal that effect the solubility of the iron lead to corrosion. Cinders, scraps of metal, and organic material may create differences of potential and thus cause corrosion. Stray currents from electric generators have been, in the past, an important cause of severe corrosion. This cause has diminished in importance during the last decade, but is still important in some localities. Differences of potential resulting from the way in which the metal was made are of only minor importance. Cases of segregation, improper heat treatment, poor or dirty material, etc., occasionally occur, but they are responsible for only a small percentage of losses due to corrosion. The use of materials unsuited to their environment is a much more frequent cause. The interconnection of different metals, such as the use of copper service pipe with iron water mains, occasionally results in corrosion. Anaerobic bacteria may be indirect causes of corrosion under certain conditions because their life processes depolarize cathodic areas. It is a question whether so-called long-line currents are the cause or the result of corrosion. The origin of these currents, which are frequently observed in cross-country pipe lines, is in doubt as they could result from one or more of several causes.

3. CHARACTERISTICS OF SOILS AS CORROSIVE ENVIRONMENT

(a) CLASSIFICATION

The fact that the rate of corrosion and the depth and distribution of pits are different in different soils suggests the possibility that there may be a definite correlation between the type of soil and its corrosive action. A soil may be considered as a chemical that attacks a metal placed in it. However, the percentage of chemically active materials in most soils is very low and thus the solution is very weak. On the other hand, the chief factor in most underground corrosion is differential aeration. The distribution of air or oxygen and carbon dioxide in a soil, as well as the amount and distribution of moisture and ionized salts and acids, varies widely with the type of soil. For this reason, corrosion is more severe in some types of soils than in others.

It should be pointed out that, in the strictly technical sense, the material in a trench in which a pipe is laid loses its identity as a soil when its structure is changed by the shovel or ditching machine. The structure of the backfill depends not only upon the soil in which the trench is located, but also upon the way in which the soil was handled. Nevertheless, the characteristics of the soil are important factors, and its classification can be very helpful in connection with the maintenance of pipe lines.

A soil may be defined as two or more layers of finely divided, modified rock material having well-defined characteristics. In general, the term "soil" is applied to the first few feet of material covering the level and moderately inclined portions of the earth. Crushed rock and unmodified rock on mountain tops are not soils and, strictly speaking, earth removed from its original position is not soil if it has lost its structure.

The classification of soils is based on their physical and chemical characteristics and not on their geologic origin or geographic location, although the soil characteristics may be influenced by both the origin and the location of the soil.

Soils may be divided broadly into two classes: those in which lime

accumulates in the subsoil (pedocals) and those in which it does not (pedalfers). In the United States the first class lies generally west of a north and south line from northwestern Minnesota to a point on the Gulf of Mexico, 100 miles north of the Mexican border. Marbut [33] has classified the well-developed soils of the continental United States into eight great soil groups, to which he has added several groups of

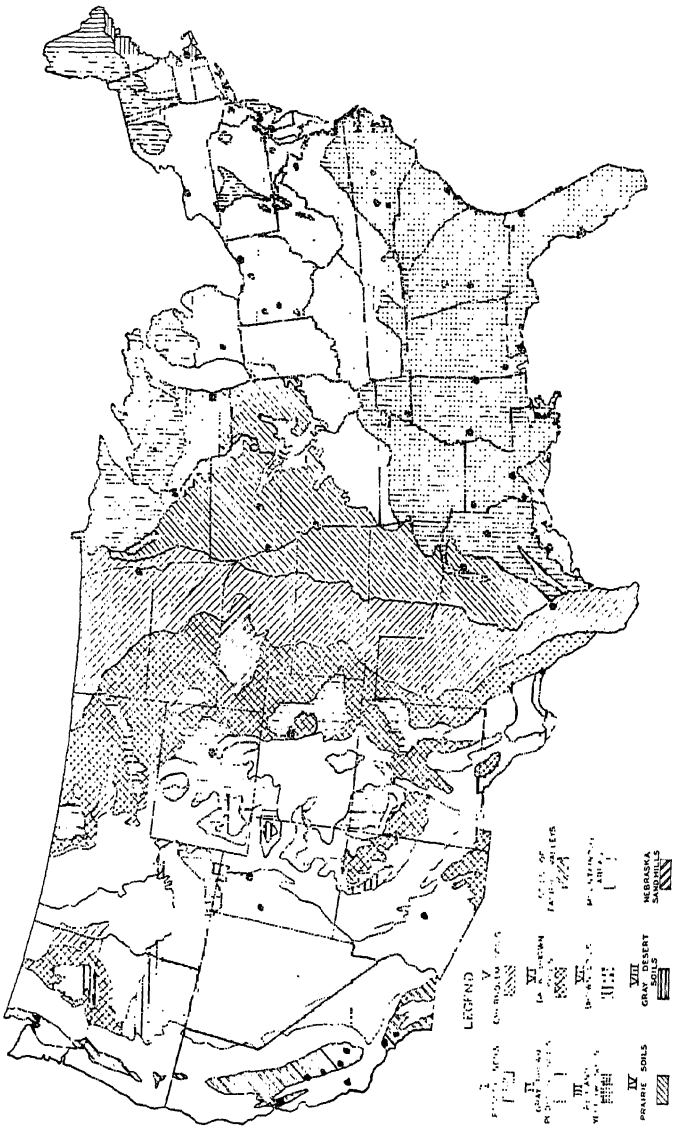

FIGURE 1.—*Soil groups of the United States.*
The dots show the location of the National Bureau of Standards test sites.

undeveloped soils, among which are muck, peat, rough stony land, sand, and some others. Figure 1 shows the boundaries of the great soil groups, as defined by Marbut. Table 1 lists Marbut's great soil groups, briefly describes typical soil profiles, and gives some of the types represented

TABLE 1.—*Description of typical profiles in great soil groups, and classification of soils in which the National Bureau of Standards test sites are located.*

Class	Soil groups	Description of profile	Reaction of profile	Soil type
I	Podsol	A_0, a few inches of leaf mat A_1, very thin dark-gray A_2, whitish-gray, a few inches thick B_1, dark- or coffee-brown B_2, yellowish-brown	Strongly acid	None.
I	Brown podsolic	A_0, leaf mat and acid humus A_1, thin, dark-gray A_2, thin, gray-brown or yellowish-brown B, brown, only slightly heavier than surface soil	Acid	Gloucester sandy loam. Merrimac gravelly sandy loam.
II	Gray-brown podsolic	A_0, thin leaf litter and mild humus. A_1, dark-colored, 2 to 4 inches thick A_2, grayish-brown, leached horizon extending to 8 to 10 inches B, yellowish-brown to light reddish-brown, definitely heavier in texture	do	Hagerstown loam. Chester loam. Sassafras silt loam. Miami clay loam. Lindley silt loam.
II	Yellow podsolic	A_0, thin, dark-colored organic covering A_1, pale yellowish-gray leached layer 6 inches to 3 feet thick B, heavy, yellow C, red and gray mottled parent material (acid)	do	Kalmia fine sandy loam. Norfolk sandy loam. Ruston sandy loam.
III	Red podsolic	A_0, thin organic layer A_1, yellowish-brown or grayish-brown leached layer B, deep-red C, mottled, red, yellow, and gray.	Acid	Cecil clay loam. Memphis silt loam. Susquehanna clay.
IV	Prairie	A, very dark brown or grayish-brown B, brown C, light-colored parent material at 2 to 5 feet	Slightly acid surface soil. Neutral to alkaline subsoil.	Marshall silt loam. Summit silt loam.
V	Chernozem	A, black or very dark grayish-brown friable soil to a depth ranging from 3 to 4 feet B, light-colored to whitish lime accumulation	Alkaline	Fargo clay loam.
VI	Dark brown soils	A, dark-brown or dark grayish-brown B, light-gray or white calcareous material at 1½ to 2 feet	do	
VII	Brown soils	A, brown B, light-gray or white calcareous layer at 1 to 2 feet	do	
VIII	Gray desert soils	A, light grayish-brown or gray, low in organic matter B, light in color, high in lime, often high in soluble salts	do	Mohave sandy loam. Panoche clay loam.
VIII	Soils of Pacific valleys	A, brown, reddish-brown or red, friable soil B, heavy, tough, more intense in color	Neutral to slightly alkaline	Ramona loam.
VIII	Rendzina (immature soils developed from marl)	A, dark-gray or black granular soil B, soft, light-gray calcareous material	Alkaline	Houston black clay loam.
VIII	Alluvial soils			Genesee silt loam. Miller clay. Sharkey clay. Wabash silt loam.
VIII	Saline soils	A, light-colored ashy material B, darker-colored heavy material of columnar structure	do	Docas clay. Fresno fine sandy loam.

in the National Bureau of Standards tests. Baldwin, Kellogg, and Thorp [34] in general followed Marbut's grouping of soils but have added several groups. It was not practicable at the time this Circular was prepared to classify all the soils in which test sites have been established by the Bureau.

According to the practice of the U. S. Department of Agriculture, the surface layer, or horizon, is designated by the letter A, the subsoil by B, and the partly weathered parent material by C.

Each great soil group contains from 9 to 60 subgroups known as soil series, each of which is further subdivided as to the texture of the uppermost horizon. The three horizons comprising the profile of most soil types may differ widely in texture, color, and composition. A soil name consists of two parts—the first designates the series and the second the type. The series name is usually taken from the name of the locality where the series was discovered. The type name describes the texture of the top, or A, horizon. More than 200 soil series have been identified in the United States. Considerably more than two-thirds of the tillable soil of the United States has been mapped. Soil reports[4] are issued for single counties or similar political subdivisions. Each report contains descriptions of the soil types and a map that shows in color the locations of the soil types within the area. The reports do not discuss the corrosivity of the soils, but they are, nevertheless, very helpful, as the pipe-line engineer can learn from them the aeration, drainage, and other characteristics of the soil that affect corrosion along his right-of-way. Unfortunately, most of the desert and mountain lands where oil and gas are frequently found have not been mapped. The soils of the older cities have not been mapped, but soil surveys of cities would be of little value because of the disturbing effects of cuts, fills, pavements, and buildings.

The texture of a soil horizon is determined by the percentages of the particles of various size groups. As to particle size, there are two grand subdivisions—those materials having diameters of 2 millimeters (0.079 inch) or more, which includes gravel, cobbles, and larger stone, and a group of materials of smaller diameter subdivided as indicated in table 2.

TABLE 2.—*Classification of soil particles as to size.*

Class	Diameter, millimeters
Gravel and stones	>2
Fine gravel	1 to 2
Sand	0.05 to 1
Silt	0.002 to 0.05
Clay	<0.002

Marbut has classified soils as to texture as follows:

I. Sands include all soils containing 20 percent or less of silt and clay, the rest of the material being sand.
   1. Coarse sands contain 35 percent or more of fine gravel and coarse sand and less than 50 percent of other grades of sand.
   2. Medium sands contains 35 percent or more of fine gravel, coarse and medium sand, and less than 50 percent of other grades of sand.

[4] Soil survey reports may be secured from the Superintendent of Documents, Government Printing Office, Washington 25, D. C. Give name of county and State.

3. Very fine sands contain 50 percent or more of very fine sand.

II. Sandy loams contain from 20 to 50 percent of silt and clay. They are designated as coarse, medium, fine, and very fine sandy loams in accordance with the predominant sand class group present. There are also gravelly loams and stony loams.

III. Loams and clays contain 50 percent or more of silt and clay combined.

1. Loams contain 20 percent or less of clay, from 30 to 50 percent of silt, and from 30 to 50 percent of sand.
2. Silt loams contain 20 percent or less of clay, 50 percent or more of silt, and 30 percent or less of other classes.
3. Clay loams contain from 20 to 30 percent of clay, from 20 to 50 percent of silt, and from 20 to 50 percent of sand.
4. Clays contain 30 percent or more of clay and 70 percent or less of other classes.

The classification of soils as to texture is shown in figure 2. This figure

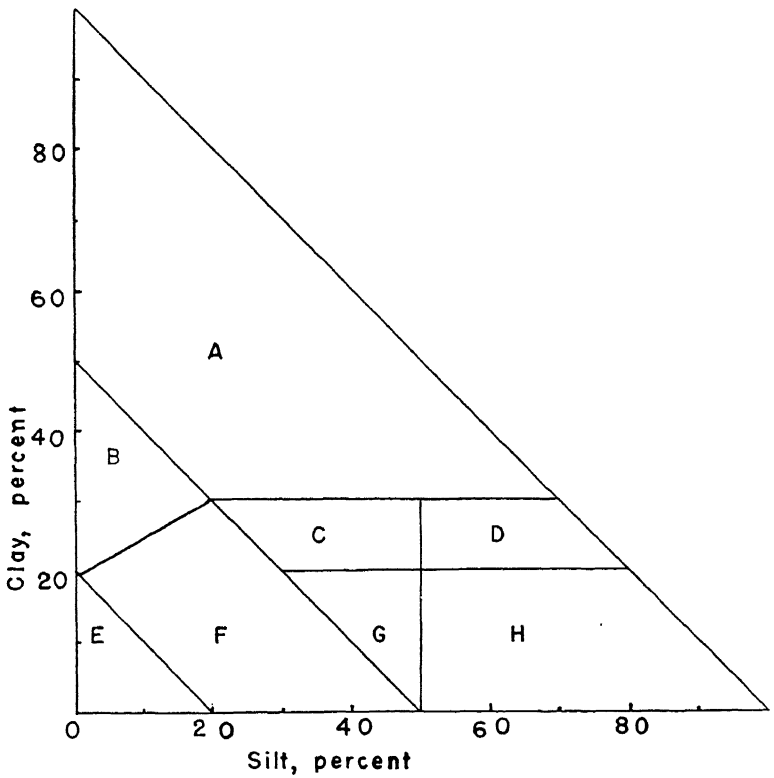

FIGURE 2.—*Whitney diagram for classifying soils according to their clay and silt content.*

The texture of the soils is determined by the area in which the clay and silt ordinates intersect: *A*, clay; *B*, sandy clay; *C*, clay loam; *D*, silty clay loam; *E*, sand; *F*, sandy loam; *G*, loam; *H*, silt loam.

shows only the percentages of clay and silt. Their sum subtracted from 100 gives the percentage of sand.

The A horizon, the texture of which determines the soil type, is usually less than a foot in thickness and may differ in many ways from the

horizon below it, in which pipes are commonly laid. Beneath the true soil are one or more layers of unconsolidated material from which the soil is being slowly formed. As pipes usually do not lie in the A horizon, the name of the soil type does not indicate the texture of the soil to which the pipe is exposed. However, as a soil with a given name is always substantially the same wherever it occurs, the name of the soil does disclose to those familiar with its significance the character of the soil in all its parts. Thus, wherever found, the light-textured A horizon of Susquehanna sandy loam is underlain by a heavy, impervious clay subsoil. The Norfolk sandy loam, on the other hand, always has a friable sandy clay subsoil. Consequently, by reading the soil descriptions which accompany the soil maps, the pipe-line engineer can determine whether a section of his line will be exposed to a poorly drained soil, where corrosion is likely to be bad and where soft coatings would be distorted, or to a well-drained soil, where little corrosion is to be anticipated.

(b) CHEMICAL PROPERTIES

Although a very large number of chemical elements exist in soils, most of them are combined in difficultly soluble compounds, which exert little chemical influence on corrosion. These inert components of soils are chiefly combinations of oxygen with silicon, aluminum, and iron. Iron in various degrees of oxidation is responsible for the color of many soils, and this color is an indicator of the degree of aeration of the soil.

Chemical analyses of soils, from the standpoint of corrosion, are usually limited to determinations of the composition of the solution resulting from the contact of water and soil under standard conditions. The base-forming metals usually looked for are sodium, potassium, calcium, and magnesium. The acid radicals sought are carbonate, bicarbonate, chloride, nitrate, and sulfate. Usually the hydrogen-ion concentration of the solution, or the total acidity of the soil, or both, are determined.

The development of acidity in soils is a result of the natural processes of weathering under humid conditions. In regions of moderate rainfall, soluble salts do not accumulate except where soil waters seep to lower levels and collect in depressions. However, in regions of high rainfall, not only are soluble salts removed from the soil but also the absorbed bases normally in the colloidal materials of the soil are partially removed and replaced with hydrogen ions. This process eventually gives rise to the condition known as soil acidity. The depths to which this replacement of bases occurs varies with rainfall, drainage, type of vegetation, and nature of the material present. The fully developed soils of the prairie regions are acid to a considerable depth, whereas soils whose development has been retarded by poor drainage or other conditions are alkaline and may even contain appreciable quantities of salts. East of the prairies the well-developed soils are acid throughout the soil profile.

The soluble constituents of soils affect corrosion because they control the potentials of the anodes and cathodes and the resistance of the path of the corrosion current. The soluble constituents, especially the salts, furnish most of the ions which carry the current. As a rule, soils containing considerable quantities of salts in solution are corrosive.

Corrosion is also affected by the reactions between the soluble salts and the primary products of corrosion, the effect on the rate of corrosion depending on whether or not the reaction products are precipitated and on the location of the deposited products with respect to the anode

and cathode of the corrosion circuit. In general, if the reactions result in the formation of soluble products, or if the products are precipitated at a distance from the electrodes, corrosion continues.

If insoluble, poorly conducting products are deposited on one or both of the electrodes, corrosion will be retarded. For example, iron continues to corrode in soils containing sodium chloride because the anodic corrosion product, ferrous chloride, and the cathodic product are both soluble. On the other hand, if calcium bicarbonate is present, difficultly soluble calcium carbonate is precipitated at the cathodic areas because of the increase in alkalinity in that region resulting from the flow of current. As a result of this deposit the current is reduced and the rate of corrosion decreases. However, if salts forming soluble corrosion products are present, the beneficial effect of calcium carbonate is largely nullified.

If iron is placed in a soil containing a soluble sulfate, corrosion progresses as in the presence of sodium chloride, but if lead is substituted for iron, corrosion ceases after a short time because of a deposit of insoluble lead sulfate.

Table 3 shows the composition of the water extracts from five of the least corrosive soils in the original National Bureau of Standards soil-corrosion tests and from five of the most corrosive soils in the same tests. The table also shows the maximum pit depths on the 12-year-old Bessemer steel specimens exposed to these soils, and the electrical resistivity of the soils. Analyses were not made of soils of high electrical resistivity because of the very low concentration of soluble material in these soils.

The rate of corrosion is affected by the time of exposure and the area of the specimen exposed. The apparent relative merits of materials with respect to corrosion may change with the duration of the exposure because of the development or breakdown of corrosion products. Likewise, the apparent relative corrosiveness of two soils with respect to a material may change with the period of exposure because of the effect of the soils on the development of protective corrosion products or the exhaustion of corrosive elements in one of the soils. For this reason, table 3 also includes five of the least corrosive soils and five of the most corrosive soils, based on the estimated time required for 1,000 feet of 8-inch steel pipe having a wall thickness of 0.322 inch to be punctured by corrosion. The paper [35] from which the data were taken indicates that the estimates are very rough. It will be noted that the corrosive soils are considerably lower in resistivity and higher in salt content than the less corrosive soils.

The effect of acidity on the corrosion of ferrous metals in soils and in natural waters is much the same as that of salts, such as sodium chloride, as the effect in both cases is to increase the solubility of the corrosion products. Baylis [36] has pointed out that the tendency of iron to go into solution would be a function of the hydrogen-ion concentration if there were rapid displacement of the solution and no tendency to form a surface coating. Whitman, Russell, and Altieri [37] and Whitman and Russell [38] found that in a solution free from salts which form protective coatings, the corrosion rate of steel was unaffected by the hydrogen-ion concentration between pH 9.5 and pH 4, but was determined by the rate at which oxygen diffused to the cathodic surface and by the protectiveness of the film formed on the metal surface. The protective action of this film in water having a pH as low as 4 was attributed to the fact that the quantity of hydrogen ions

TABLE 3.—*Composition of water extracts of some corrosive and noncorrosive soils.*[a]

[mg-eq = milligram equivalent]

No.	Soil: Type	Corrosivity: Maximum pit depth after 12 years	Corrosivity: Life of pipe	Electrical resistivity	Acidity: pH	Acidity: Total mg-eq per 100 g of soil	Composition of water extract, mg-eq per 100 g of soil: Na + K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4
	LEAST CORROSIVE WITH RESPECT TO MAXIMUM PIT ON 126 IN.² OF BESSEMER STEEL AT 12 YEARS												
		Mils	*Years*	*Ohm-cm*									
47	Unidentified silt loam	29	.....	1,770	7.6	3.0	0.67	0.72	0.39	0.00	0.88	0.06	0.48
24	Merrimac gravelly sandy loam	31	.....	11,400	4.5	12.6	.....	.....	.....	.....	.....	.....	.....
26	Miami silt loam	39	.....	2,980	7.3	2.6	.27	.50	.31	.00	.70	.03	.12
6	Everett gravelly sandy loam	40	.....	45,000	5.9	12.8	.....	.....	.....	.....	.....	.....	.....
31	Norfolk fine sand	45	.....	20,500	4.7	1.8	.....	.....	.....	.....	.....	.....	.....
	MOST CORROSIVE WITH RESPECT TO MAXIMUM PIT ON 126 IN.² OF BESSEMER STEEL AT 12 YEARS												
23	Merced (alkali) silt loam	173	.....	278	9.4	[b]A	8.38	0.38	0.22	0.02	1.87	1.12	5.57
28	Montezuma (alkali) clay adobe	153	.....	408	6.8	([c])	1.50	.06	.18	.00	0.12	0.99	0.89
29	Muck	146	.....	1,270	4.2	28.1	2.15	1.92	1.55	.00	.00	1.69	2.30
45	Alkali soil (unidentified)	137	.....	263	7.4	A	8.15	3.70	0.70	.00	.24	0.18	11.98
8	Fargo clay loam	119	.....	350	7.6	A	1.42	1.72	2.55	.00	.71	.01	4.43
	LEAST CORROSIVE WITH RESPECT TO LIFE OF 1,000 FT OF 8 IN. STEEL PIPE (BASED ON EWING'S EQUATION)[d]												
31	Norfolk fine sand	.....	∞	20,500	4.7	1.8	.....	.....	.....	.....	.....	.....	.....
6	Everett gravelly sandy loam	.....	do	45,000	5.9	12.8	.....	.....	.....	.....	.....	.....	.....
24	Merrimac gravelly sandy loam	.....	9×10^6	11,400	4.5	12.6	.....	.....	.....	.....	.....	.....	.....
36	Ruston sandy loam	.....	5×10^4	11,200	4.5	4.6	.....	.....	.....	.....	.....	.....	.....
17	Keyport loam	.....	9×10^3	5,980	4.5	19.1	.....	.....	.....	.....	.....	.....	.....
	MOST CORROSIVE WITH RESPECT TO LIFE OF 1,000 FT OF 8 IN. STEEL PIPE (BASED ON EWING'S EQUATION)												
29	Muck	.....	7	1,270	4.2	28.1	2.15	1.92	1.55	0.00	0.00	1.69	2.30
23	Merced (alkali) silt loam	.....	8	278	9.4	A	8.38	0.38	0.22	.02	1.87	1.12	5.57
28	Montezuma clay adobe (alkali)	.....	10	408	6.8	([b])	1.50	.06	.18	.00	0.12	0.99	0.89
33	Peat	.....	13	800	6.8	36.0	1.52	7.30	4.06	.00	.....	2.27	2.13
45	Alkali soil (unidentified)	.....	16	263	7.4	A	8.15	3.70	0.70	.00	.24	0.18	11.98

[a] Analyses by I. A. Denison.
[b] A indicates alkaline.
[c] Not determined.
[d] See reference [35] for discussion of Ewing's equation.

coming in contact with the metal surface was insufficient to neutralize and dissolve the film. However, when carbon dioxide was introduced rapid corrosion occurred at pH 5.4 because then the increased total acidity of the water was sufficient to neutralize the hydroxide film. This result led to the conclusion that total acidity is more important in corrosion by natural waters than is the actual concentration of hydrogen ions, that is, the pH value.

As the acids in soils are only slightly dissociated, the pH value of a soil may offer no indication of the capacity of the acidic material to prevent the formation of otherwise protective hydroxide films. An acid soil having a relatively high pH value and a high total acidity would be expected to be more corrosive than a soil having a lower pH value and a lower total acidity because of the greater tendency of high total acidity to prevent the formation of protective films. Denison and Hobbs [39] found a correlations between total acidity and the corrosiveness of soils with respect to steel, both in the field and in the laboratory, under conditions in which other causes of corrosion were nearly constant. This correlation was confirmed by Denison and Ewing [40], who obtained the correlation shown in table 4 between total acidity and replacements for a pipe line in Ohio. It will be noted that in the absence of other variables, the corrosiveness of the soils increased with their acidity. However, the standard deviation of the average percentage of repairs shows that even within a single type of soil the corrosion varies greatly.

TABLE 4.—*Relation of acidity to pipe line repairs in different types of soils.*

Soil type	Total acidity	Standard error	Repairs	Standard deviation
	mg-eq	*Percent*	*Percent*	*Percent*
Wauseon fine sandy loam[a]	7.5	.....	6.3	.....
Canaedea silt loam	12.7	2.1	13.3	11.0
Miami silt loam	16.8	2.8	22.8	30.6
Mahoning silt loam	18.1	0.7	20.9	13.3
Trumbull clay loam	21.1	2.3	20.0	20.0
Crosby silt loam	22.0	1.2	30.8	16.9

[a] One sample.

In certain regions of the Midwest and Pacific Coast a correlation has been found between soil resistivity and corrosion, the soils having the lowest resistivity being the most corrosive. As the conductivity of the soils is entirely electrolytic, the amount and kinds of salts in solution would largely determine the resistivity of the soil, and the corrosivity of the soil would increase with the salt content.

(c) PHYSICAL PROPERTIES

The physical properties of soils that are of importance in corrosion are chiefly those which determine the aeration of the soil and its retentiveness for water. The texture of the soil, which is determined by the percentages of the particles of the various size groups, is obviously an important factor with respect both to aeration and to moisture content. In soils of coarse texture, such as sands and gravels, in which there is free circulation of air, corrosion approaches the atmospheric type. However, in heavy clay soils, which are usually very retentive of water, corrosion proceeds in an atmosphere very deficient in oxygen, thereby tending to approach the condition of submerged corrosion. There are, however, differences between corrosion processes in water and in soil. Some of these occur because soils are much less homo-

geneous than water. Other differences occur because corrosion products diffuse more slowly in soils, as convection currents and other movements of water are retarded by soil particles. Moreover, corrosion tests in water usually involve a single corrosive agent, whereas in soils several different factors influence corrosion and may react on each other. For these reasons great care should be exercised in applying the results of tests in water to corrosion in soils.

Corrosion is retarded by the oxidation of corrosion products that produce films or thicker deposits. These deposits either reduce the differences of potentials between anodic and cathodic areas or interpose electric resistance which reduces the corrosion current. The degree to which oxidation occurs depends largely on how readily oxygen can reach the corroding metal, which is determined by the permeability of the different soil horizons both above and below the buried metal and the rainfall and drainage of the region. In general, the aeration of clay soils is poor, whereas that of sandy soils is usually good. However, low-lying sands, and sands underlain by a consolidated stratum or a hard-pan layer, may be poorly aerated for long periods in regions where the rainfall is heavy.

As the aeration of the soil, which is the chief factor in the supply of oxygen and carbon dioxide, is determined not only by the character of the soil but also by the amount of water that the soil contains, the aeration will vary from season to season and cannot be expressed exactly or numerically, except perhaps for some temporary condition.

In well-aerated soils the rate of pitting of ferrous metals is initially very high because of the abundant oxygen supply at the cathodic areas. However, oxidation and consequent precipitation of the corrosion products in close contact with the anodic areas cause a marked reduction in the rate of corrosion with the result that the ultimate depth of pitting is relatively slight. On the other hand, in poorly aerated soils the rate of pitting, although low because of deficiency of oxygen at the cathodic areas, is relatively unchanged with time, because the corrosion products in the reduced condition are precipitated at points remote from the anodic areas. Consequently, the depths of the deepest pits after a long period are usually considerably greater in poorly aerated soils than in well-aerated soils.

Some soil water occupies the larger spaces between the soil particles, holes left by decaying roots, etc. This part of the soil moisture varies greatly with the season, rainfall, and drainage. Water also adheres closely to the minute soil particles, and is removed from them and the small soil capillaries only with difficulty. On this account, well-drained soils retain a certain amount of moisture even through long periods of drought.

Other physical properties of soils that are of importance in soil corrosion are air-pore space, apparent specific gravity, water-holding capacity, moisture equivalent, and shrinkage. The air-pore space is the percentage of the volume of soil at a definite moisture content that is occupied by air. It is therefore a relative measure of the permeability of the soil to air and of the rate at which moisture can move through the soil. Other things being equal, a high value of air-pore space indicates a relatively noncorrosive soil. The apparent specific gravity, which is the weight of a unit volume (1 ml) of undisturbed soil, is an index of the compactness of mineral soils because the true specific gravity of the mineral particles in soils varies only within narrow limits. This

value is influenced to a large extent by the amount of voids in the soil. The moisture equivalent of a soil is defined as the percentage of water retained by a previously saturated layer of soil of given weight when subjected to a centrifugal force of 1,000 times gravity. The moisture equivalent is a measure of the retentiveness of soils for water. The quantity of water retained by soils when equilibrium with capillary and gravitational forces has been established is the water-holding capacity of the soil.

The volume shrinkage is a measure of the colloidal nature of the particles in a soil and indicates the tendency of the soil to crack on drying and to swell when wetted. The cracking of soil permits more oxygen to reach buried pipe and so affects the character of the corrosion products and the differential aeration potentials. Some soils on drying form hard clods which at times act much like stones with respect to differential aeration and pressure on pipe coatings. Some soils adhere tightly to certain pipe coatings, and as they shrink on drying tend to pull the coating from the pipe [41]. Some coatings are pressed into the soil cracks when the soil expands due to the absorption of water. Figure 3 shows cracks in Lake Charles clay soil and ridges in a rag-felt-reinforced asphalt coating caused by soil pressure. Thus soil shrinkage is important to corrosion and pipe-line protection. In general, clay soils and soils high in organic matter shrink the most, but not all clay soils shrink greatly on drying. For example, Bell clay has a clay content of 44.9 percent and a shrinkage value of 23 percent, whereas Susquehanna clay has a clay content of 45.8 percent and shrinks only 4.7 percent. Fargo clay loam has a clay content of 70.1 percent and a shrinkage of 21.0 percent.

The physical properties of soils are described by Keen [42]. This publication, however, does not discuss the relations of the physical properties of soils to corrosion. The chemical and physical properties of soils, as well as their origin and classification, are discussed in the Atlas of American Agriculture [33] and Soils and Men [43, 44], but neither of these books discusses soil corrosivity.

The physical characteristics of soils that are favorable to corrosion are poor aeration, and high values for moisture equivalent, clay content, apparent specific gravity, and shrinkage. These are characteristics of heavy, poorly drained soils. They are not independent of each other, and their effects on corrosion may be modified by the chemical characteristics. Table 5 shows the relative corrosivity of some of the soils in the National Bureau of Standards tests, as indicated by the average of four criteria [45] and the values of some of the physical properties of those soils.

Soils differ greatly in corrosiveness, and their corrosivity is affected by many soil properties. Table 6 shows the maximum and minimum values of certain data on soils at National Bureau of Standards test sites. The range of values for all soils in this country is considerably greater. Widely different soils frequently are found within a few hundred feet of each other, and corrosive soils are found in most parts of the United States.

As soil characteristics differ greatly and corrosive soils are widely distributed, it is obvious that no average value for the corrosiveness of soils and no allowance or factor of safety based on average soil conditions should be used in the design of a pipe line to be installed under specific soil conditions. It is necessary in each case to consider the cor-

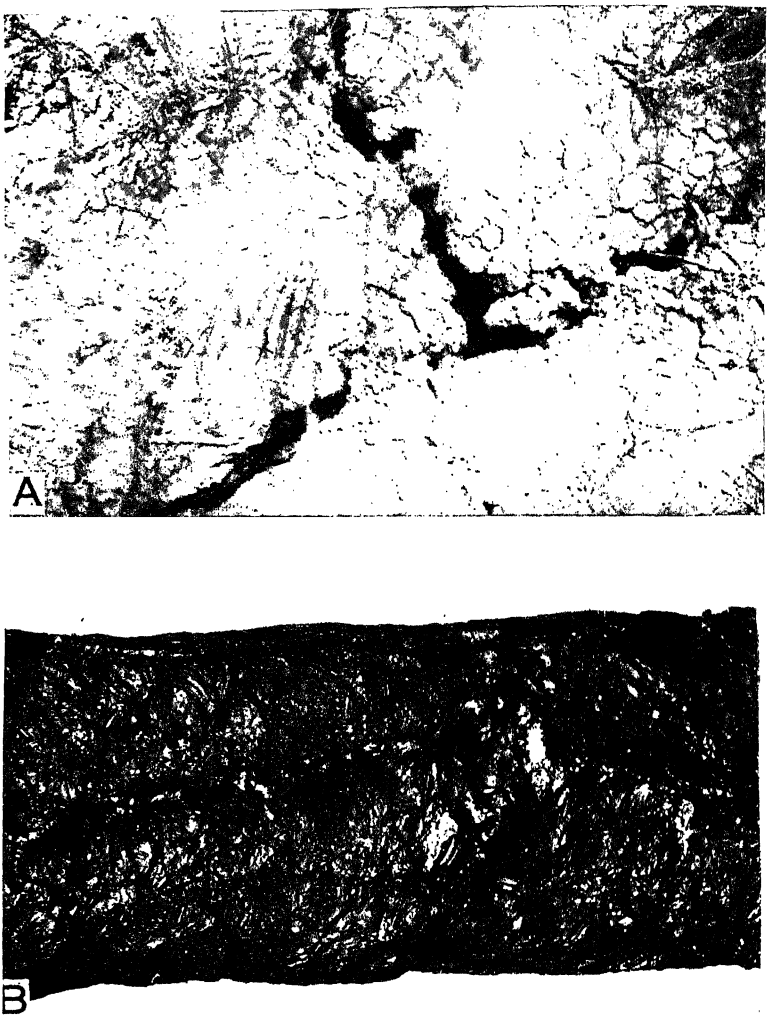

FIGURE 3.—*Soil cracking and its effect on a pipe coating.*

A, Cracks in Lake Charles clay. The white spot below the junction of the cracks is a fifty-cent coin; *B*, rag felt reinforced asphalt pipe coating wrinkled by soil pressure. Swelling of the soil forced the coating into the cracks. Note also cracks in the coating.

rosiveness of the soils that the pipe line will encounter if proper account of soil corrosion is to be taken. Any other procedure must result in waste on parts of the line and inadequate protection for other parts.

As many of the factors that influence corrosion are not closely related and do not vary together, one cannot expect to find a close correlation between corrosion and any single soil characteristic. It is important to remember this when soil surveys and corrosivity tests are considered.

IV. INVESTIGATIONS BY THE NATIONAL BUREAU OF STANDARDS

1. GENERAL PLAN AND METHODS

In 1921 the American Committee on Electrolysis, of which the National Bureau of Standards was a member, decided that the effect of

TABLE 5.—*Correlation of soil corrosivity with the physical properties of soils.*

Relative corrosiveness	Soil number	Moisture equivalent (compacted soil)	Aeration[a]	Air-pore space	Apparent specific gravity	Volume shrinkage	Resistivity at 60° F (15.6° C)
		Percent		*Percent*		*Percent*	*Ohm-cm*
1	[b]28	19.6	VP	2.5	(c)	5.9	408
2	43	(c)	VP	(c)	(c)	(c)	60
3	14	12.2	F	14.4	1.76	1.0	3,520
4	4	22.2	P	7.0	1.78	2.2	6,670
5	40	31.0	P	2.3	1.78	16.4	970
6	42	24.8	F	14.9	1.79	4.7	13,700
7	37	7.0	F	(c)	(c)	0	11,200
8	8	34.8	P	8.7	1.56	21.0	350
9	11	31.3	G	15.5	1.49	8.6	11,000
10	16	16.5	F	12.0	1.65	0.6	8,290
11	39	18.3	P	7.5	1.72	3.8	7,440
12	41	28.1	F	6.9	1.61	14.6	1,320
13	44	25.3	G	7.2	1.55	6.0	1,000
14	3	29.9	G	18.2	1.60	7.0	30,000
15	30	24.0	P	7.2	1.81	7.5	1,500
16	32	11.8	G	11.7	1.85	0.1	5,700
17	19	26.3	F	3.9	1.76	11.8	1,970
18	2	35.2	P	2.0	1.95	23.0	684
19	22	28.4	G	9.6	1.67	3.0	5,150
20	18	22.0	G	16.6	1.26	1.3	1,410
21	25	18.6	F	9.5	1.95	7.6	1,780
22	7	36.4	P	3.7	2.02	34.5	2,120
23	36	14.9	G	16.0	1.62	0	11,200
24	17	27.7	P	4.4	1.72	5.4	5,980

[a] VP = very poor; P = poor; F = fair; G = good.
[b] Most corrosive soil.
[c] Not determined.

TABLE 6.—*Maximum and minimum values of certain properties of the soils at the National Bureau of Standards test sites.*[a]

Property		Maximum value	Minimum value
Electrical resistivity	Ohm-cm	54,400	32
Moisture equivalent	%	75.5	2.3
Air-pore space	%	40.6	1.1
Apparent specific gravity	%	2.08	1.41
Volume shrinkage	%	42.7	0
Total acidity	mg-eq/100 g of soil	297.0	0
pH		10.2	2.6
Annual precipitation[b]	in.[2]	61.6	2.0
Mean air temperature[b]	°F	71.8	39.
Composition of water extract:			
Na + K as Na	mg-eq/100 g of soil	45.1	[c]0
Ca	do	19.24	0
Mg	do	9.45	0
CO_3	do	4.6	0
HCO_3	do	2.1	0
Cl	do	43.3	0
SO_4	do	46.5	0

[a] Determinations by I. A. Denison, R. B. Hobbs, and I. C. Frost.
[b] Data furnished by United States Weather Bureau.
[c] Zero values are estimated from the specific resistance of the soil.

soils on pipe unexposed to stray electric currents should be investigated, and the Bureau undertook the project. Soon thereafter the committee became inactive, and some years later it disbanded.

The original purpose of the soil-corrosion investigation was to determine the extent to which soils free from currents from street railways and other sources of power were corrosive with respect to the metals commonly placed in them. It is important to remember this objective, as it explains many things with respect to the conduct of the investigation. The reader should also bear in mind that many phenomena related to

the behavior of metals in soils were not generally understood at the time the tests were undertaken.

The next step in the investigation was a meeting of the technical representatives of a number of manufacturers of cast and wrought ferrous pipe with representatives of the National Bureau of Standards. At this meeting an agreement was reached as to the sizes and varieties of materials for the initial tests and the way in which the specimens should be buried. The Bureau of Soils, now the Bureau of Plant Industry, Soils, and Agricultural Engineering, of the United States Department of Agriculture, acted as an adviser in the selection of the types of soils to which the specimens should be exposed and assisted in the selection of the test sites in order that, insofar as was practicable, the sites should represent definite soil types. However, in order to secure labor and keep down expenses, it was sometimes necessary to use sites that were not altogether satisfactory, and which might have been rejected had the importance of very uniform soil conditions been fully realized.

Each time specimens were removed, manufacturers and other cooperators were invited to have representatives present to note soil conditions and the condition of the specimens. On each occasion one and usually several cooperators' representatives participated in the removal of the specimens. A rough draft of the report on the specimens was submitted to each manufacturer concerned, and usually a conference was held for the purpose of discussing and revising the report. In this way the Bureau obtained the advice and suggestions of a large number of experts in different phases of corrosion. With a very few exceptions, the revised reports had the approval of all concerned. The so-called National Bureau of Standards soil-corrosion investigation is therefore more than the name implies, and the results can be accepted with a considerable degree of confidence, provided the way in which they were obtained is fully understood.

The cooperators in the investigation are listed in Appendix 1. Each cooperator has been listed only once, although many of them have cooperated in several ways and in several tests. The soils where the specimens were buried are described in Appendix 2.

Figures 4 to 6 illustrate the ways in which the specimens were placed in the trenches. The depths at which the specimens were placed corresponded roughly to the depths at which pipes had been laid in the same region, and ranged from 18 inches in the southern locations to 6 feet in northern locations. Before the specimens were buried, careful tests were made for stray electric currents. The specimens were placed in a definite order with respect to each other and from 6 inches to 1 foot apart to avoid one specimen affecting the corrosion of another and to facilitate the removal of one set of specimens without disturbing the soil near the other sets. When the specimens were removed, the upper side or edge of each was marked with a center punch. This made it possible to study the distribution of corrosion on each specimen with respect to its position in the trench, and with respect to other specimens.

As a rule, 10 or 12 specimens of each material were buried at each test site, and 2 specimens were removed at intervals of approximately 2 years. In later years the times between removals were modified in accordance with the apparent corrosiveness of the soil to which they were exposed. The removal of specimens after different periods of exposure was to obtain data on changes in rates of corrosion. It was hoped that the life of a pipe of a given wall thickness could be predicted from these changes.

FIGURE 4.—*Burial of soil corrosion specimens near Alexandria, Va., in 1922.*

After the specimens were removed from the trench, the loose dirt was scraped off and the specimens were boxed and returned to the National Bureau of Standards. Most specimens having protective coatings terminated in caps that supported the specimens and prevented the coatings from touching the box or each other during shipment. When the specimens reached the laboratory, each different material was subjected to appropriate chemical and mechanical treatments, to remove the corrosion products with an insignificant loss in weight of the base metal and without mechanical injury to the specimen. The methods employed in cleaning the specimens are described in detail in Appendix 3, and the methods of obtaining, computing, and reporting the data are described in Appendix 4. Careful tests showed that the wrought ferrous specimens lost very little metal by the cleaning processes. The penetration of corrosion on cast iron is along the boundaries between the graphite and the metal crystals and some uncorroded iron probably was removed with the corrosion products. On the other hand, tests showed that usually not quite all the corrosion products were removed by cleaning the specimens.

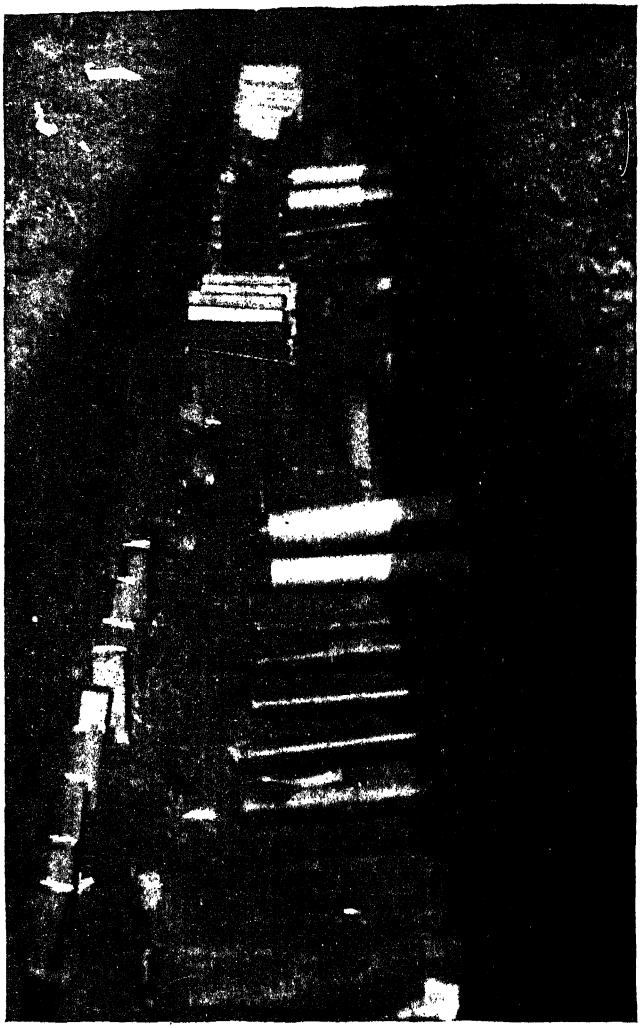

FIGURE 5.—*Arrangement of specimens buried in 1924*
Note two soil horizons.

The soil-corrosion investigation started with the burial of only the most commonly used pipe materials and coatings. From time to time, as specimens were removed, other materials were added to the tests. By 1932 it had become evident that the corrosion of the commonly used ferrous pipe materials was rapid in some soils, and a new series of tests was started for the purpose of finding materials suitable for use in corrosive soils. For these tests 15 corrosive soil test sites were chosen, and manufacturers were invited to submit materials which they believed suitable for corrosive-soil conditions. This considerably increased the already long list of materials under observation and introduced a few materials that were unsuitable for testing by the methods applied to ferrous pipe. New pipe coatings were also submitted, although previous tests had shown that tests of coatings applied to short lengths of pipe served only

FIGURE 6.—*Arrangement of specimens buried near Baltimore, Md., in 1932.*

to eliminate definitely unsuitable coatings and were insufficient to identify coatings that would effectively protect operating pipe lines.

2. MATERIALS TESTED

Tables 7 to 18 show the form, dimensions, composition, and the number of specimens of each material submitted for the National Bureau of Standards tests, and also the coatings tested by the American Gas Association (AGA) and the American Petroleum Institute (API) under the direction of the Bureau. Tests have been started on more than 36,000 specimens. At present, about 6,500 specimens remain exposed to 17 soils.

It will be noted in the tables that the same letter has been used to designate different kinds of materials. The identification of the material involves an identifying letter, the name of the class of materials to which the specimen belongs, and the year in which the specimen was buried. The form, dimensions, and age of a specimen are also helpful for determining the group to which the specimen belongs. As the specimens are grouped as to age and material in all the soil-corrosion reports, readers of the reports should have little difficulty on account of the identification of the specimens.

TABLE 7.—*Composition*

Material	Identification	Year buried	Number of specimens buried	Form	Nominal width or diameter
					in.
Wrought iron:					
Hand-puddled	b, d	1922	564	Pipe	1.5
Do	B, D	1922-28	742	do	3
Do	A	1932	150	do	1.5
Roe process	B	1932	150	do	1.5
Carbon steels, wrought iron and pure open-hearth iron:					
Pure open-hearth iron	A	1924	40	Sheet	2.0
Open-hearth iron	a	1922	568	Pipe	1.5
Do	A	1928	174	do	3
Open-hearth steel	K	1922	568	do	3
Bessemer steel	e	1922	568	do	1.5
Do	y	1922	568	do	1.5
Do	M, N	1922-28	888	do	3
Low-carbon steel	N	1932	150	do	2.5
Low-alloy irons and steels:					
Copper-bearing steel	Y	1922	568	Pipe	3
Do	S	1924	40	Sheet	2.0
Special open-hearth steel	A	1937	150	Plate	2.5
Copper-molybdenum open-hearth iron	M, M	1939	150	do	2.5
Do	O	1937	150	do	2.5
Do	N	1937	150	do	2.5
Do	H	1932	150	Pipe	1.5
Do	H	1941	150	do	1.5
Copper-nickel steel	J	1937	150	Plate	2.5
Nickel-copper steel	B	1937	150	do	2.5
Do	Y	1941	150	Pipe	2.0
Do	D	1932	150	do	1.5
Chromium-silicon-copper phosphorus steel	C	1937	150	Plate	2.5
2% chromium steel with molybdenum	N, N	1939	150	Pipe	1.5
2% chromium steel with molybdenum	K, K	1937	150	Plate	2.5
4 to 6% chromium steels:					
4 to 6% chromium steel	P	1932	150	Pipe	2.3
Do	D	1937	150	Plate	2.5
4 to 6% chromium steel with molybdenum	E	1937	150	do	2.5
4 to 6% chromium steel with molybdenum	H	1937	150	do	2.5
High-chromium steels:					
12% chromium steel	U	1932	175	Sheet	4
18% chromium steel	V	1932	175	do	4
Do	X	1932	60	Pipe	1.5
26% chromium	C	1926	66	do	1
High-chromium-nickel and manganese steels:					
18% chromium steel with nickel	K	1932	150	Sheet	3
18% chromium steel with nickel	R	1932	60	Pipe	1.5
18% chromium steel with nickel	W	1932	175	Sheet	4
18% chromium steel with nickel and manganese	T	1932	25	do	6
18% chromium steel with nickel and manganese	S	1932	30	do	6
18% chromium steel with nickel, manganese and molybdenum	C, M	1939	150	Plate	2
20% chromium steel with nickel, manganese and molybdenum	D, T	1939	150	do	2.5
22% chromium steel with nickel and manganese	Y	1932	175	Sheet	4

of wrought ferrous materials.

Length	Thickness	C	Si	Mn	S	P	Cr	Ni	Cu	Mo	Other elements
in.	*in.*	%	%	%	%	%	%	%	%	%	%
6	0.145	0.03	0.15	Trace	0.023	0.145	.....	.....	0.02	....	.....
6	.216	.02	.15	0.033	.022	.195	.....	.....	.03	....	.....
12	.145	.016	.10	0.29	.018	.160	.....	.....	.....	....	Oxide+slag 2.56
12	.145	.017	.125	0.41	.018	.106	.....	.....	.....	....	Oxide+slag 2.681
6	.125	.....	.....	.....	.....	.....	.....	.....	.....	....	Fe 99.9
6	.145	.02	.09	Trace	.05	.01	.....	.....	.014	....	.....
6	.216	.02	.09	do	.05	.01	.....	.....	.....	....	.....
6	.216	.12	.....	.41	.036	.043	.....	.....	.....	....	.....
6	.145	.09	.....	.39	.040	.088	.....	.....	.....	....	.....
6	.145	.....	.....	.38	.050	.092	.....	.....	.....	....	.....
6	.216	.08	.....	.40	.038	.098	.....	.....	.....	....	.....
10	.145	.15	.....	.49	.030	.013	.....	.....	.....	....	.....
6	.216	.07	.....	.24	.032	.008	.....	.....	.22	....	.....
6	.062	.....	.....	.....	.....	.....	.....	.....	.....	....	.....
12	.188	.033	.002	.029	.017	.006	0.049	0.034	.052	....	.....
12	.25	.04	.....	.16	.027	.008	.04	.14	.051	0.07	O_2, 0.015 N_2, 0.008 Sn, 0.002
12	.25	.03	.003	.16	.032	.007	.02	.15	.45	.07	.....
12	.25	.06	.001	.098	.029	.069	.02	.14	.54	.13	.....
12	.145	.04	.05	.32	.027	.016	.....	.....	.52	.15	.....
.....	.145	.036	.005	.16	.025	.008	.....	.....	.47	.08	.....
12	.265	.06	.047	.49	.025	.095	.....	.52	.95	....	.....
12	.248	.07	.14	.44	.022	.010	.....	1.96	1.01	....	.....
8.5	.154	.12	.12	.58	.025	.07	.....	1.95	1.04	....	.....
12	.145	.14	.19	.21	.....	.....	.....	2.47	1.08	....	.....
12	.188	.075	.84	.20	.018	.124	1.02	0.22	0.428	....	.....
14.5	.145	.09	.25	46	.010	.015	1.96	.....	.....	.49	.....
12	.175	.082	.51	.46	.015	.017	2.01	.07	.004	.57	.....
10	.154	.13	.....	.46	.025	.012	5.05	.....	.....	....	.....
12	.245	.077	.43	.37	.005	.015	5.02	.09	.008	....	.....
12	.188	.074	.41	.32	.006	.013	4.67	.09	.004	.51	Al, 0.030 Ti, 0.022
12	.203	.060	.39	.40	.014	.021	5.76	.17	.004	.43	Al, 0.27
6	.063	.065	.28	.38	.017	.011	11.95	.482	.025	....	.....
6	.063	.070	.34	.36	.015	.014	17.08	.092	.021	....	.....
12	.145	.12	.277	.42	.017	.016	17.72	.287	.....	....	.....
6	.250	.....	.....	.....	.....	.....	26	.....	.....	....	.....
11	.025	.08	.33	.44	.022	.015	17.20	8.95	.....	....	.....
12	.145	.05	.28	.46	.011	.015	17.52	8.85	.....	....	.....
6	.063	.093	.42	.36	.017	.008	18.69	9.18	.016	....	.....
10	.063	.06	.40	6.09	.....	.....	17.76	3.83	.95	....	.....
10	.063	.07	.48	9.44	.....	.....	17.78	.....	.74	....	.....
12.5	.25	.07	.40	1.24	.008	.016	17.78	10.96	.....	2.63	.....
12	.25	.07	.91	1.99	.012	.014	19.27	22.12	1.07	3.52	.....
6	.063	.144	.59	1.80	.011	.015	22.68	12.94	.021	....	.....

TABLE 10.—*Composition of zinc, lead, and aluminum-alloy materials.*

Material	Identification	Year buried	Number of specimens in test	Form	Nominal width or diameter	Length	Thickness	Zn	Al	Cu	Fe	Pb	Sn	Bi	Sb	Si	Mn	Other elements
					in.	*in.*	*in.*	%	%	%	%	%	%	%	%	%	%	%
Zinc:																		
Rolled zinc	Z	1937	150	Plate	2.3	12	0.15	.....	.....	.....	0.009	0.095	.....	.....	.....	.....	.....	0.0038 Cd.
Die casting zinc	CZ	1937	150	do	4.44	6.8	.122	.....	4.00	1.05	.018	<.003	<0.001	.....	.....	.....	.....	0.003 Cd.
Standard zinc[a]	P	1924	40	Sheet	2.0	6	.062	99.+	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.02 to 0.05 Mg.
Zinc	Z_1	1924	40	do	2.0	6	.062	99.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Do	Z_2	1924	40	Plate	2.0	6	.25	99.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Lead:																		
Hearth refined lead	NN	1924	40	Plate	2.0	6	.25	.....	.....	0.002	.....	99.99	.....	0.004	.....	.....	.....	.....
Chemical lead	N	1924	40	do	2.0	6	.25	.....	.....	.57	.....	99.93	.....	.....	.....	.....	.....	.....
Do	O	1937	150	Pipe	1.5	12	.177	.....	.....	.056	.....	99.94	.....	.002	0.0011	.....	.....	0.009 Ag.
Tellurium lead	T	1937	150	do	1.5	12	.177	.....	.....	.082	.....	99.87	.....	.....	.0011	.....	.....	.....
Antimonial lead	A	1922	281	Sheet	8.5	22	.12	.....	.....	.062	.....	99.12	.....	.....	82	.....	.....	.043 Te.
Do	B	1937	150	Pipe	1.5	12	.177	.....	.....	.036	.....	99.64	.....	0.016	5.31	.....	.....	.....
Commercial lead	H	1922	281	Sheet	3.5	22	.11	.....	.....	.013	.....	99.95	.....	.037	.....	.....	.....	.....
Lead alloy	M	1941	150	Pipe	1.25	15	.172	.....	.....	.....	.....	.....	0.25	.....	.....	.....	.....	0.02 Ca; 0.02 Mg, plus usual impurities in lead.
Aluminum:																		
Commercial aluminum	C_1	1924	40	Sheet	2.0	6	.062	.....	99.25	.09	.33	.....	.....	.....	.....	0.3	0.03	.....
Aluminum with manganese	C_2	1924	40	do	2.0	6	.062	0.02	97.75	.16	.51	.....	.....	.....	.....	.44	1.12	.....
Duralumin	C_3	1924	40	do	2.0	6	.062	.....	94.23	4.10	.30	.....	.....	.....	.....	.23	0.62	0.52 Mg.

[a] Standard composition.

TABLE 11.—*Metallic-coated specimens.*

Material	Identification	Year buried	Number of specimens buried	Form	Nominal width or diameter	Length	Wall thickness	Average weight of coating	Average thickness of coating
					in.	*in.*	*in.*	*oz/ft²* [a]	*in.*
Zinc coatings:									
Bessemer steel	B	1922	124	Pipe	2.0	24	0.154	1.81	0.0032
Pure open-hearth iron	A	1923	208	do	2.0	17	.154	2.82	.0050
Wrought-iron	D	1923	24	do	3.0	17	.216	3.48	.0061
Do	D	1923	28	do	1.5	17	.145	4.99	.0088
Copper-bearing open-hearth steel	Y	1923	56	do	3.0	17	.216	3.47	.0061
Pure open-hearth iron	A_2	1924	28	Sheet	6	12	.062	1.79	.0032
Do	A_3	1924	188	do	6	12	.062	1.98	.0035
Do	A_4	1924	28	do	6	12	.062	2.65	.0047
Copper-bearing steel	Y_2	1924	28	do	6	12	.062	1.57	.0028
Do	Y_3	1924	188	do	6	12	.062	2.15	.0038
Do	Y_4	1924	28	do	6	12	.062	2.76	.0048
Do	Y_5	1924	28	do	6	12	.062	2.92	.0051
Bessemer steel	B	1924	188	do	6	12	.062	1.62	.0028
Pure open-hearth iron	[b]CA	1924	56	do	6	12	.050	1.87	.0033
Bessemer steel	[b]CB	1924	56	do	6	12	.050	1.66	.0029
Copper-bearing steel	[b]CY	1924	56	do	6	12	.050	2.12	.0037
Steel	[c]T	1937	300	Pipe	1.5	14	.145	3.08	.0052
Lead coatings:									
Steel	L	1924	376	do	1.5	6	.145	.....	.0025
Do	CA	1932	150	do	1.5	13	.145	.....	.0015
Aluminum coatings:									
Wet calorized	.....	1924	48	Pipe	2.0	6	.154	.....	.....
Dry calorized	.....	1924	56	do	2.0	6	.154	.....	.....
Tin coating:									
Tinned copper	.....	1937	150	do	1.5	12	.060	.....	.....

[a] 1 oz/ft² of surface = 0.00172 in.
[b] Uncoated black sheets buried for controls.
[c] Black iron pipe buried for controls.

TABLE 12.—*Nonbituminous-nonmetallic coatings.*

Identification	Year buried	Number of specimens	Average thickness	Description[a]
			in.	
B.....	1932	150	.....	A synthetic rubber, stated to be an olefin polysulfide reaction product, was exposed in the form of sheets 10 by 5 by ¼ inch. Subsequently, a process was developed which permitted application of this material to pipes. Specimens coated by this process were exposed in 1939.
C.....	1932	150	0.014	Two coats of porcelain enamel, one of which was acid-resisting.
D.....	1932	150	.010	First coat, 23-percent solution of a rubber derivative in xylene; second and third coats, 30-percent solution of the rubber derivative in xylene; fourth coat, 20-percent solution of the rubber derivative in a mixture of turpentine and mineral spirits. Five percent of the solids was carbon black.
E.....	1932	150	.005	Two applications of paint that differed in color. Neither the kind of pigment nor the kind of vehicle was specified.
F.....	1932	150	.060	A semiplastic compound, which was applied cold with a brush, consisting of 4½ parts of treated cashew-nutshell oil, 3 parts of asbestos fiber, and 3½ parts of mineral turpentine substitute.
G.....	1932	60	.090	A hard-rubber compound, containing rubber, sulfur, and an accelerator, cured to a bone-hard condition.
H.....	1932	60	.100	A highly loaded hard-rubber stock which contained 30 percent of magnesium carbonate and approximately 15 percent of "white substitute."
J.....	1932	30	.....	A synthetic resin varnish baked at 425° F for 30 minutes.
K.....	1932	30	.006	A paint containing highly chlorinated rubber, dissolved in a suitable solvent, to which may have been added drying oils, pigments, quarts meal, or carborundum. This coating was applied in Germany to pipe 1 inch in outside diameter.
W.....	1932	150	.170	An experimental coating prepared as follows: The pipe was primed with a china-wood-oil varnish containing zinc chromate and basic lead chromate and baked at 200° F for ½ hour. A top coat of dehydrated china-wood oil containing powdered mica and a catalyst was molded on the pipe and heated to 200° F for 3 hours.
L.....	1937	150	.007	Two coats of a Bakelite varnish followed by two coats of another type of Bakelite varnish, each coat being baked after spraying. It appears as though the baking has resulted in a fusion of the separate layers.
M_1....	1937	150	.004	Two coats of a Bakelite priming followed by two coats of a bakelite chemically resistant aluminum paint. Each coat was sprayed and allowed to air dry overnight. More specifically the priming consisted of a Bakelite 25-gallon varnish—55 parts, zinc chromate, 30 parts, asbestine, 15 parts, to which was added lead-cobalt-manganese drier. The finishing aluminum paint consisted of 2 pounds of aluminum paste to a gallon of a Bakelite chemically resistant varnish.
M_2....	1937	150	.003	The same as coating M_1, except that it was applied to 2½ by 12-inch plates instead of to pipe.
N.....	1937	150	.032	A double layer of Bakelite-treated asbestos tape, the second layer overlapping the first, which was made to adhere to the pipe and to the first layer of tape by the use of an anticorrosive resin compound. A final protective coat was used over this tape, consisting of a spray coat of the same Bakelite chemically resistant aluminum enamel as used on the M_1 specimens.
P.....	1937	50	.033	A fabric coated on one side with Koroseal to an over-all thickness of 0.03 inch. The fabric was wrapped spirally on the pipe under tension with the Koroseal next to the metal and then painted with two coats of Koroseal solution applied hot.
R.....	1939	150	.0055	A blue basic lead sulfate phenolic resin varnish paint consisting of two coats of the following composition: Basic lead sulfate in raw linseed oil (90% pigment)....100 lb. Lampblack in raw linseed oil (2% pigment)..... 3 lb. China-wood oil 100% phenolic resin varnish (33-gallon length).....23.9 lb.
S.....	1939	150	.044	Plastic made of pure vegetable gum base with nondrying oils and asbestos fiber applied cold. Shielded by a spiral wrap of impregnated cotton fabric.
T.....	1939	45	.035	Thiokol sprayed on.

[a] The coatings were applied to 1½-inch standard pipe, 12 inches in length, unless otherwise stated. The descriptions of the coatings were furnished by the manufacturers.

TABLE 13.—*Miscellaneous specimens included in the National Bureau of Standards tests.*

Symbol	Material	Year buried	Number of specimens buried
A	Decarburized, malleable-iron nuts and bolts	1932	48
B	Not decarburized, malleable-iron nuts and bolts	1932	48
C	High-strength, malleable-iron nuts and bolts	1932	48
D	Steel nuts and bolts	1932	48
CD	Charcoal cast-iron nuts and bolts	1939	150
CE	Steel nuts and bolts	1939	150
E	Sheradized nuts and bolts	1924	100
	Lead-coated nuts and bolts	1924	96
	Black wrought-iron nuts and bolts	1924	100
E	2-inch cast steel elbows	1924	56
I	4-inch machined cast-iron pipe	1924	24
V	2-inch semisteel nipples	1924	48
S	2-inch malleable-iron bends	1924	48
	1½-inch couplings attached to threaded pipe	1922	192
P	Composite steel plates	1941	150
	Miscellaneous Bureau of Mines zinc plates	1924	27
C	1-inch chrome iron pipe	1926	66
C	2-inch copper-steel pipe	1926	20
D	2-inch machined wrought-iron pipe	1926	18
K	2-inch unfinished wrought-iron pipe	1926	18
L	2-inch leadized pipe	1926	42
M	2-inch machined Bessemer steel pipe	1926	18
P	2-inch unfinished Bessemer steel pipe	1926	18
	Four different mixtures of pipe fittings (brass caps attached to lead, brass, and galvanized nipples)	1924	2,208
	11 types of bituminous coatings	1924	976
	Armoured cable	1924	246
	American Gas Association bituminous-coating tests[a]	1929	2,352
	American Petroleum Institute bituminous-coating line tests[b]	1930	2,050
	American Petroleum Institute bituminous-coating nipple tests[b]	1930	2,208
	Asbestos-cement flue pipe	1932	150
	6-inch asbestos-cement pipe, class 150	1937	150
	4-inch asbestos-cement pipe, class 150	1939	150
I	Cement-coated cast iron	1924	52

[a] See tables 17 and 18 for description and characteristics of these coatings.
[b] See tables 14, 15, and 16 for description and charactertistics of these coatings.

TABLE 14.—*Coatings in American Petroleum Institute line tests.*

Symbol	Thickness	Description
	in.	
A.....	0.0647	Two coats of asphalt emulsion.
B.....	.1072	One coat of grease, spiral wrap of grease-saturated fabric (Osnaburg type), and outer coat of heavier-consistency grease.
C.....	.0206	Two coats of filled cutback coal tar.
E.....	.1506	Asphalt primer, followed by sling coat of asphalt compound, spiral wrap of coal-tar-saturated Osnaburg fabric, outer coat of asphalt and kraft paper.
F.....	.4185	Two coats of asphalt emulsion, followed by rigid shield of sand and cement mortar.
G.....	.0625	Coal-tar primer, followed by coal-tar-asphalt enamel, and unbonded wrap of asbestos pipe-line felt.
H.....	.0807	Coal-tar primer, followed by coal-tar enamel, and unbounded wrap of wood veneer.
K.....	.0685	Coal-tar primer, followed by coal-tar-asphalt enamel.
L.....	.0798	Coal-tar primer, followed by coal-tar enamel.
M.....	.0576	Do.
N.....	.0596	Coal-tar primer, followed by coal-tar-asphalt enamel.
O.....	.5186	Asphalt primer, followed by a hot coat of priming asphalt, and spiral wrap of asphalt mastic carried on pipe with tissue and sheathing paper (machine-applied).
R.....	.1427	Asphalt primer, followed by two coats of asphalt enamel; spiral application of asbestos pipe-line felt; flood coat of enamel, and kraft paper (machine applied).
S.....	.1502	Asphalt primer, followed by two coats of asphalt; spiral application of rag-base pipe-line felt; flood coat of asphalt, and kraft paper (machine-applied).
T.....	.3507	Coal-tar primer, followed by two straight-away rag-base pipe-line felt applications on the inner faces of which coal-tar enamel mopped on; sling coat of coal-tar enamel, and whitewash.
U.....	.1709	Coal-tar primer, followed by two coats of coal-tar-asphalt enamel; spiral application of asbestos pipe-line felt; flood coat of enamel, and kraft paper (machine-applied).
X.....	.2302	Hot asphalt primer, followed by double-spiral wrap of unsaturated fabric (Osnaburg type) drawn through molten asphalt, and spiral-butt wrap of 26-gage strip steel.
Y.....	.0287	Asphalt primer, followed by one coat of asphalt cutback; one coat of asphalt adhesive, and machine-wrap of aluminum foil.
Z.....	.2062	Hot asphalt primer, followed by double-spiral wrap of unsaturated fabric (Osnaburg type) drawn through molten asphalt, and kraft paper (machine-applied).

TABLE 15.—*Coatings on American Petroleum Institute short pipe sections.*

Symbol	Sponsor	Average thickness	Description
		in.	
a	American Tar Products Co.	0.054	Pyrmax primer, followed by one coat of Komac P. C. enamel (coal tar).
b	Arco Co.	.020	Two coats of filled Arco Q. D. Savaline (cutback coal tar).
bb	do	.034	One coat of filled Arco Q. D. Savaline; spiral wrap of saturated fabric (Osnaburg type); and final coat of Savaline.
c	Barber Asphalt Co.	.072	Asphalt primer, followed by two spiral wraps of saturated fabric (Osnaburg type), and kraft paper—Genasco pipe-coating type 1—(fabric and kraft paper machine-applied).
cc	do	.045	Two coats of cutback asphalt—Genasco pipe-coating type 2.
d	The Barrett Co.	.342	Barrett coal-tar primer, followed by two coats of rag-base roofing felt to the inside face of which hot Barrett pipe-line enamel (coal tar) was mopped on, and an outer coat of enamel followed by whitewash.
dd	do	.050	Barrett coal-tar primer, followed by Barrett pipe-line enamel (coal tar) and whitewash.
ddd	do	[a].050	Barrett coal-tar primer, followed by Barrett pipe-line enamel (coal tar) and unbonded polymerized resin shield.
e	Dearborn Chemical Co.	.026	One coat of No-Ox-Id G special, spiral wrap of grease-saturated fabric (Osnaburg type), and outer coat of service coat (heavier-consistency grease).
ee	do	.022	Same as e excepting impregnated asbestos-base roofing felt used in place of woven fabric.
f	E. I. duPont de Nemours and Fibrkote Co.	.149	Two coats of asphalt-chromate emulsion, spiral-butt wrap of asbestos pipe-line felt, outer coat of A.C.E. and whitewash.
ff	do	.190	Two coats of asphalt-chromate emulsion followed by a coat of sand and cement mortar.
fff	do	.037	Two coats of asphalt-chromate emulsion (whitewashed).
g	Eagle Picher Lead Co.	.069	Under coat of sublimed blue lead followed by bitumastic primer (coal tar) and bitumastic XXH (coal-tar enamel). See coating zzz.
h	Benjamin Foster Co.	.069	Asphalt primer followed by one sling coat of I.B.M. bituminous pipe coating No. 4 (asphalt mastic).
j	Headley Emulsified Products Co.	.015	Three coats of Headley No. 11 asphalt emulsion.
k	Hill, Hubbell and Co.	.075	Biturine primer, followed by sling coat of biturine No. 212 enamel (coal-tar–asphalt).
kk	do	.165	Biturine primer followed by two coats of biturine No. 212 enamel (coal-tar–asphalt), spiral wrap of J.M. 15-lb asbestos pipe-line felt, flood coat of enamel, and kraft paper (machine-applied).
l	Inertol Co.	.081	Inertol No. 49 primer followed by two coats of seal coat (cutback asphalt) and kraft paper (kraft paper machine-applied).
m	Andrew McLean Co.	.089	Priming coat of zinc chromate, followed by McLean's asphalt emulsion and wrapped with asphalt-saturated burlap and kraft paper (burlap and kraft machine-applied).
n	Everlast, Inc.	.158	McEverlast penetration followed by a coat of hot blended compound (asphalt), spiral wrap of coal-tar-saturated Osnaburg fabric, outer coat of H.B.C. and kraft paper (fabric and kraft paper machine-applied).
nn	do	.337	Asphalt primer, followed by hot coat of priming asphalt and spiral wrap of Somastic (asphalt mastic, carried on pipe with tissue and sheathing paper (machine-applied).
p	Lead Industries Assn.	.071	One coat of red-lead paint, followed by bitumastic primer and bitumastic XXH (coal-tar enamel). See coating zzz.
pp	do	.138	One coat of red-lead paint followed by coating q.
ppp	do	.015	Priming coat of red-lead paint followed by two coats of Headley No. 11 (asphalt emulsion).

TABLE 15.—*Coatings on American Petroleum Institute short pipe sections*—Continued.

Symbol	Sponsor	Average thickness	Description
		in.	
q.....	National Tube Co.....	.155	Hot Robertson asphalt, followed by double-spiral wrap of unsaturated fabric (Osnaburg type) drawn through molten Robertson asphalt and kraft paper (machine-applied).
qq.....	....do.....	.216	Same as coating q, excepting 26-gage strip steel substituted for kraft paper.
qqq....	....do.....	.183	Hot Robertson asphalt, followed by extruded National mastic (asphalt).
r.....	Fish-Schurman Corp.....	.105	One coat of grease, followed by spiral-wrap of Denso-Tek protective tape (grease-saturated Osnaburg-type fabric), and outer coat of asphalt-saturated burlap.
s.....	Resistcor Engineering Corp...	.041	Resistcor primer (coal tar) followed by sling coat of Resistcor enamel (coal-tar–asphalt).
ss.....	....do.....	[a].041	Resistcor primer (coal-tar asphalt) followed by sling coat of Resistcor enamel (coal tar) and unbonded wrap of J.M. 15-lb asbestos pipe-line felt.
t.....	Sherwin-Williams Co.....	.052	Lynkote primer (coal tar), followed by sling coat of Lynkote enamel (coal tar).
u.....	James B. Sipe and Co.....	.047	Impervobond No. 411-083 (asphalt primer), followed by cutback-asphalt compound sprayed on.
v.....	Standard Oil Co. of California.	.337	Same as nn, using asphalt-mastic pipe coating.
vv.....	....do.....	.079	Asphalt primer, followed by Sonamel (asphalt-enamel) tissue paper, and kraft.
w.....	Standard Oil Co. of New Jersey.	.092	Asphalt primer and two coats of Standard pipe coating (asphalt-enamel).
ww....	Johns-Manville Corp. and Standard Oil Co. of New Jersey.....	.170	Asphalt primer, followed by one coat of Standard pipe coating (asphalt-enamel), spiral application of J.M. 15-lb asbestos pipe-line felt; flood coat of enamel, and kraft paper (fabric machine-applied).
x.....	Technical Products Co., Inc., Aluminum Co. of America..	.018	Tec-Pro primer (asphalt), followed by one coat of Tec-Pro black line No. 45 (asphalt cutback) and Tec-Pro adhesive (asphalt) and machine-wrap of aluminum foil.
y.....	The Texas Co.....	.144	Texaco primer (asphalt), followed by two coats of Texaco No. 30 asphalt pipe coating, spiral wrap of Texaco pipe-line felt (asphalt-saturated rag-base); flood coat of asphalt and kraft paper (machine-applied).
yy.....	....do.....	.199	Texaco primer (asphalt), followed by two coats of Texaco No. 30 asphalt pipe coating, spiral wrap of Texaco pipe-line felt; coat of asphalt, second ply of felt and kraft paper (machine-applied).
yyy....	....do.....	.259	Same as coating yy, excepting a flood coat of Texaco No. 30 asphalt pipe coating over second ply of felt. Outer wrap of kraft paper.
yx.....	Udylite Process Co.....	.0004	Electrodeposited cadmium-udylite. Cadmium.
z.....	Wailes Dove-Hermiston Corp.	.072	Bitumastic primer, followed by sling coat of bitumastic XH enamel (coal tar) and whitewash.
zz.....	Wailes Dove-Hermiston Corp. Merchants Basket and Box Co.....	[a].077	Bitumastic primer (coal tar) followed by sling coat of bitumastic XXH enamel (coal tar) and unbonded wrap of Becker's sewed wood veneer.
zzz....	Wailes Dove-Hermiston Corp.	.077	Bitumastic primer, followed by sling coat of bitumastic XXH enamel and whitewash.
zx.....	....do.....	.012	Two coats of bitumastic No. 4 (cutback coal tar).

[a] Without shield, felt, or wood veneer.

TABLE 16.—*Characteristics of bituminous coating materials in the American Petroleum Institute tests.*

[Determinations by H. S. Christopher]

Designation of material	Specific gravity	Ring-and-ball softening point	Penetration (Dow) at 115° F in 5 sec (50 grams)	Ductility (Dow) at 115° F	Consistometer hardness (Abraham) at 115° F	Insoluble in CS_2[a]	Ash[a]
		° F		*cm*		*Percent*	*Percent*
E	1.028	186	20	14.0	14.7	2.12	0.98
G, N	1.420	202	3	0.7	67.1	42.9	26.5
H, L	1.628	205	2	3.9	54.8	55.4	37.8
K, U	1.266	192	16	16.0	23.5	29.1	18.9
M	1.418	145	83	60.0	44.5	37.4	22.9
S	0.996	194	..	3.2	10.9	1.0	0.4
T	1.350	191	..	4.1	63.5	34.1	14.4
X, Z	0.997	238	16	2.5	17.1	0.7	0.13
a	1.300	241	..	2.7	34.5	42.8	10.9
d, dd	1.360	190	..	3.6	56.5	32.7	13.2
g, zz, zzz	1.610	205	2	3.8	61.3	55.6	35.3
h	1.685	189	21	10.3	13.0	61.6	61.3
k, kk	1.259	192	27	62.0	9.1	21.9	5.6
n	1.032	190	14	12.6	16.9	4.6	2.4
q, qq	1.006	232	33	2.5	16.0	0.8	0.4
s, ss	1.421	195	2	2.8	63.0	40.6	26.9
t	1.420	158	25	58.2	10.0	39.3	21.4
vv	1.050	320+	..	0.0	36.7	17.0	13.4
w, ww	1.470	163	30	7.2	8.8	42.2	39.9
y, yy, yyy	1.011	189	..	3.2	10.9	1.1	0.5
z	1.638	222	0	1.7	65.4	57.6	40.2

[a] When differences between the insoluble in CS_2 and ash are greater than 4 percent, the difference is apparently due to free carbon (a constituent of coal tar).

TABLE 17.—*Descriptions of pipe coatings in*

Symbol	Manufacturer or agent	Nature of base primer[b]	Method of applying primer	Trade name of primer	Method of applying coating
A.....	Am. Tar Products Co.	p	Brush	A. T. P. primer	Sling
B.....	Barrett Co.	p	..do.....	B. P. L. primer	..do
BB...	..do.....	p	..do.....	..do.....	Hand
C.....	Benjamin Foster Co.	a	Dipped, no other treatment.	.....	.....
CC...	..do.....	a	Brush-hot	I. B. M. No. 1	Machine
D....	DearbornChem.Co.	g	Brush	No-Ox-Id A special	Hand
DD...	..do.....	g	..do.....	No-Ox-Id G special	..do.....
E.....	Emulsion Process Co.	a	..do.....	E. P. No. 1	Brush
EE...	Consolidated Gas Co. of N. Y.	a	Dipped and dusted with cement.	.....	.....
F.....	Flintkote Co. and E. I. duPont de Nemours & Co.	a	Dipped vertically, no other treatment.	.....	.....
FF...	..do.....	a	Brush	A. C. E. +cement	Brush
G....	Headley Good Roads Co.	a	..do.....	Headley No. 11	..do.....
H....	Hill, Hubbell & Co.	p	..do.....	Inhiburine	Sling
J.....	Johns-Manville Corp.	p	..do.....	J. M. tar primer	Machine
JJ....	..do.....	a	..do.....	J.M. asphalt primer	..do.....
K....	Arco Company	p	..do.....	Arco ravenite	Brush
L.....	Barber Asphalt Co.	a	..do.....	Plastic pipe ctg.	..do.....
LL...	..do.....	a	..do.....	Genasco primer	Machine
M....	McEverlast, Inc.	a	..do.....	Penetration	Brush
MM..	..do.....	a	..do.....	..do.....	Sling and hand wrap.
N....	National Tube Co.	a	Dipped	Robertson No. 228	Machine
NL...	Lead Indus. Assn.	.....	Brush	Red lead	..do.....
NS...	National Tube Co.	a	Dipped	Robertson No. 228	Machine
NT...	..do.....	a	..do.....	..do.....	Extruded
P.....	Paraffine Co., Inc.	a	Brush	Pabco No. 440	Pabco Mach.
Q.....	Albrecht Pagenstecher.	g	Wrapped, no other treatment.	.....	Machine
R....	Resistor Eng. Corp.	p	Brush	Resist. primer	Sling
S.....	Sherwin-Williams Co.	p	..do.....	Lyne-Kote primer	..do.....
SS....	..do.....	p	..do.....	..do.....	Brush
T.....	Texas Co.	a	..do.....	Texaco primer	Machine
U....	Hill, Hubbell & Co.	p	..do.....	Inhiburine	..do.....
V.....	Iroquois Gas Corp.	a	..do.....	Robertson No. 274	Hand
VV...	..do.....	a	..do.....	..do.....	..do.....
VX...	..do.....	p	..do.....	Inertol	..do.....
W....	Wailes Dove-Hermiston Corp.	p	..do.....	Bitumastic solution	Sling
WF...	..do.....	p	..do.....	..do.....	Machine
WL...	Lead Indus. Assn.	.....	..do.....	Red lead	Sling
WR...	Wailes Dove-Hermiston Corp.	p	..do.....	Bitumastic Solution.	..do.....
WW..	..do.....	p	..do.....	..do.....	..do.....
X....	Milwaukee Gas Light Co.	a	..do.....	Pabco primer	Pabso Mach.
Y....	East Ohio Gas Co.	a	No primer	.....	Hand
Z.....	Hill, Hubbell & Co.	p	Brush	Inhiburine	Machine

[a] Final application kraft paper.
[b] a, asphalt; p, pitch; g, grease.

American Gas Association tests.

Nature of base coating[b]	Trade name of coating	Fabric reinforcement if any	Man hours to apply coating	Average temperature of application	Average thickness
				°F	in.
p	A. T. P. pipe coating No. 1.	.....	2.8	380	0.070
p	B. P. L. enamel	.....	4.0	350	.038
p	Pitch and felt	15-lb rag felt[a]	4.5	370	.134
a	I. B. M. pipe coating.	.....	3.0	.....	.014
a	I. B. M. No. 2	15-lb asbestos	7.5	375	.120
g	No-Ox-Id G	No-Ox-Id muslin	7.5	Cold	.054
g	No-Ox-Id GX +G	..do.....	10.5	280	.071
a	Parafalt	.....	4.0	Cold	.047
a	Armored hydralt	.....	1.8	...do....	.0605
a	A. C. E.	.....	4.0	...do....	.082
a	A. C. E. + cement	.....	4.0	...do....	.029
a	Headley No. 11	.....	3.75	...do....	.016
p	Biturine	.....	2.0	470	.034
p	J. M. pitch No. 2	14-lb asbestos	6.7	350	.163
a	J. M. asphalt	..do.....	7.5	475	.126
p	Save-a-line	.....	3.5	Cold	.009
a	P. P. C.	.....	2.7	...do....	.024
a	.....	Saturated cotton sheeting.[a]	5.8	..do....	.056
a	Electrolysis proof	.....	4.3	...do....	.010
a	M. P. C.	Osnaburg	5.5	375	.080
a	National coating	Muslin[a]	6.0	380	.146
a	..do.....	..do[a].....	6.25	380	.117
a	..do.....	Muslin and steel	6.0	382	.147
a	Robertson No. 230	.....	.....	340	.131
a	Floatine	Pabco felt[a]	2.2	350	.123
g	Schade's wrapper	Schade's wrapper	6.0	Cold	.051
p	Resisteor enamel	.....	2.0	400	.061
p	Lyne-Kote hot	.....	2.0	420	.034
p	Lyne-Kote cold	.....	3.0	Cold	.007
a	Texaco No. 30	15-lb rag felt[a]	8.3	450	.150
p	Biturine spec. TK-1.	30-lb rag felt[a]	3.6	425	.214
a	Robertson asphalt	Cheesecloth	2.6	420	.070
a	Std. N. J. brick filler.	..do.....	3.0	410	.038
a	..do.....	..do.....	3.0	440	.041
p	Bitumastic (XXH)	.....	3.5	456	.058
p	Bitumastic	15-lb asbestos	6.7	425	.154
p	..do.....	.....	3.2	450	.052
p	..do.....	.....	3.5	420	.0505
p	..do.....	Wood veneer	3.3	420	.100
a	Floatine	Pabco rag felt	2.0	400	.123
a	.....	Sheeting	1.7	372	.115
p	Biturine spec. TAX-1.	15-lb asbestos[a]	6.3	430	.119

TABLE 18.—*Characteristics of American Gas Association coating materials.*

Material	Penetration at—			Consistency at—			Susceptibility factor	Ductility at—			Tensile strength at—			B. & R. softening point	Ash	Insoluble in CS_2	Free carbon
	115° F	77° F	32° F	115° F	77° F	32° F		115° F	77° F	37° F	115° F	77° F	37° F				
								cm	*cm*	*cm*	*kg*	*kg*	*kg*	° *F*	%	%	%
A. T. P. pipe coating No. 1	11	2	0	27.3	57.5	103+	.....	4	0.8	0	3.3	10.0	5.4	232	1.3	36.4	35.1
BPL enamel	10	0	0	29.2	103+	103+	.....	60	.3	0	1.0	20.3	16.0	167	19.0	36.9	17.9
Barrett pitch	23	3	0	11.7	89.8	103+	.....	80	.4	0	0.8	9.2	5.4	156	0.4	19.9	19.5
IBM pipe coating	16	12	10	22.2	34.7	76.6	23.8	3	1	.5	2.5	9.7	7.5	228	4.4	4.3	.....
IBM No. 1	13	8	5	24.7	40.1	87.9	28.4	4	1	2.	3.3	12.0	5.5	223	8.7	8.4	.....
IBM No. 2	14	8	5	24.7	41.2	89.4	28.3	4	.9	0.3	3.3	10.0	10.5	229	8.9	9.4	.....
Parafalt[a]	Too soft	100 to 120	25 to 31	.....	.....	.....	.....	.....	100+	.....	.....	.....	.....	102 to 122	.....	.1–.5	.....
A. C. E.[a]	do	110 to 120	30	.....	.....	.....	.....	.....	100+	.....	.....	.....	.....	110 to 115	.....	0.2	.....
Headley No. 11[a]	240 to 260	35 to 45	5+	.....	.....	.....	.....	.....	30+	.....	.....	.....	.....	145 to 155	.....	.5	.....
Biturine from machine	24	2	1	12.4	72.1	103+	.....	45	0.4	0	1.0	10.5	5.9	162	9.1	24.7	15.6
Biturine for H coating	7	2	4	54.2	103+	103+	.....	10	0	0	10.0	5.4	8.0	187	16.2	33.8	17.6
JM pitch No. 2	58	4	1	9.4	58.5	103+	.....	25	5	0	0	17.5	19.0	159	14.5	32.7	18.2
JM asphalt	46	19	13	10.4	25.6	63.0	28.6	15	4	.8	.1	3.8	13.6	184	0.8	1.1	.....
Barber plastic pipe coating[a]	.....	30 to 40	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	135	.....	.....	.....
M. P. C.	19	5	1	13.2	60.8	103+	51.4+	48	1	0	.6	8.5	0	175	.9	2.4	1.5
Robertson 228	84	31	18	5.5	18.3	44.1	25.1	90+	11	3	.1	1.4	13.2	154	.4	0.3	.....
National saturant	37	24	19	14.8	26.2	44.5	13.8	2	3	1	.6	3.8	15.2	215	.1	.2	.....
Robertson 230	20	10	10	21.2	34.9	68.0	18.4	1	0.7	0.8	3.1	11.9	18.6	255	63.7	62.0	.....
Floatine (Pabco)	103	37	18	4.4	17.0	57.5	36.9	31	6	2	0	1.4	12.7	144	0.2	0.3	.....
Resistcor enamel	2	0	0	73.7	103+	103+	.....	1	0	0	27.0	3.6	13.0	201	25.7	43.3	17.6
Lyne-Kote hot	14	2	3	29.2	92.1	103+	.....	64	0	0	0.4	23.0	17.0	162	21.9	39.9	18.0
Texas asphalt No. 30	46	28	19	13.0	22.9	61.3	24.8	4	3	2	.3	3.9	11.6	195	0.3	0.3	.....
St. N. J. brick filler	58	27	19	10.4	22.9	59.4	27.8	25	4	0.8	.1	3.0	8.6	176	.6	.4	.....
Bitumastic XXH	2	1	2	51.9	103+	103+	.....	5	0.3	0	13.0	27+	27.0	208	36.7	55.7	19.0
Bitumastic	10	0	0	26.7	98.1	103+	.....	25	.4	0	2.0	27+	19.0	184	35.8	52.2	16.4
Floatine (Milwaukee)	64	27	14	8.0	22.2	60.8	33.8	56	6	.8	0	3.8	10.0	156	0.5	0.9	.....
East Ohio asphalt	23	13	11	18.2	32.8	74.3	25.7	4	3	1	1.6	7.8	17.7	218	.1	.2	.....

[a] Characteristics of original asphalt as given by the manufacturer.

3. SOILS AT TEST SITES

For a complete understanding of the results of the National Bureau of Standards tests, detailed information as to the conditions to which the materials were exposed is essential. Descriptions of the profiles of the test sites are therefore presented in Appendix 2.

These descriptions were prepared in most instances by soil scientists of the U. S. Department of Agriculture. In a few cases the description of the site was prepared by the man who buried the specimens. The reader will see that in many cases the test trench was not uniform in all respects throughout its length. This contributed to the dispersion of the data. Under the conditions of the test, it was impracticable to secure completely uniform sites. However, the uniformity is probably greater than that encountered by pipe lines, and the lack of uniformity calls attention to the variability in corrosion which must be expected on pipe lines. From a practical viewpoint it may be fortunate that completely uniform sites were not available, as such sites might have obscured an important characteristic of underground corrosion.

The National Bureau of Standards has conducted or supervised corrosion tests at 128 locations scattered throughout the United States. In some instances, however, two or three tests of different materials have been conducted in the same type of soil. For this reason the Bureau's tests furnish information directly on only about 95 types of soils. Table 19 shows the numbers, types, locations, and other data relating to the soils in the National Bureau of Standards tests.

TABLE 19.—*Test sites, soil numbers, types, locations, and other information relating to soils at NBS, AGA, and API test sites.*

[G, good; F, fair; P, poor; VP, very poor]

Soil[a]	Soil type	Location	Mean temperature[b]	Annual precipitation[b]	Internal drainage of test site
		NATIONAL BUREAU OF STANDARDS SITES			
			°F	Inches	
1	Allis silt loam	Cleveland, Ohio	49.2	33.8	P
2	Bell clay	Dallas, Tex.	65.5	36.2	P
3	Cecil clay loam	Atlanta, Ga.	61.2	48.3	G
4	Chester loam	Jenkintown, Pa.	54	40	F
5	Dublin clay adobe	Oakland, Calif.	56.4	23.4	P
6	Everett gravelly sandy loam	Seattle, Wash.	51.0	34.0	G
7	Maddox silt loam	Cincinnati, Ohio	53.2	38.6	F
8	Fargo clay loam	Fargo, N. Dak.	39	21	P
9	Genesee silt loam	Sidney, Ohio	51.2	39.0	P
10	Gloucester sandy loam	Middleboro, Mass.	50	41	F
11	Hagerstown loam	Baltimore, Md.	55.4	42.6	G
12	Hanford fine sandy loam	Los Angeles, Calif.	62.4	15.2	F
13	Hanford very fine sandy loam	Bakersfield, Calif.	64.6	5.6	F
14	Hempsted silt loam	St. Paul, Minn.	44.2	27.2	F
15	Houston black clay	San Antonio, Tex.	68.9	27.2	P
16	Kalmia fine sandy loam	Mobile, Ala.	67.3	61.6	F
17	Keyport loam	Alexandria, Va.	55	42	P
18	Knox silt loam	Omaha, Nebr.	50.6	27.8	G
19	Lindley silt loam	Des Moines, Iowa	49.5	32.0	G
20	Mahoning silt loam	Cleveland, Ohio	49.2	33.8	P
21	Marshall silt loam	Kansas City, Mo.	54.4	37.1	F
22	Memphis silt loam	Memphis, Tenn.	61.6	47.7	G
23	Merced silt loam	Buttonwillow, Calif.	65	6	F
24	Merrimac gravelly sandy loam	Norwood, Mass.	50	41	G
25	Miami clay loam	Milwaukee, Wis.	46.1	30.1	F
26	Miami silt loam	Springfield, Ohio	53	37	G
27	Miller clay	Bunkie, La.	67	56	P
28	Montezuma clay adobe	San Diego, Calif.	61.0	10.3	P
29	Muck	New Orleans, La.	69.3	57.4	VP
30	Muscatine silt loam	Davenport, Iowa	49.9	32.1	P
31	Norfolk fine sand	Jacksonville, Fla.	69.3	47.4	G
32	Ontario loam	Rochester, N. Y.	47.6	32.8	G
33	Peat	Milwaukee, Wis.	46.1	30.1	VP
34	Penn silt loam	Norristown, Pa.	54	40	F
35	Ramona loam	Los Angeles, Calif.	62.4	15.2	G
36	Ruston sandy loam	Meridian, Miss.	64.0	53.0	G
37	St. Johns fine sand	Jacksonville, Fla.	69.3	47.4	P
38	Sassafras gravelly sandy loam	Camden, N. J.	54	40	G
39	Sassafras silt loam	Wilmington, Del.	54	40	F
40	Sharkey clay	New Orleans, La.	69.3	57.4	P
41	Summit silt loam	Kansas City, Mo.	54.4	37.1	F
42	Susquehanna clay	Meridian, Miss.	64.0	53.0	P
43	Tidal marsh	Elizabeth, N. J.	52	43	VP
44	Wabash silt loam	Omaha, Nebr.	50.6	27.8	G
45	Unidentified alkali soil	Casper, Wyo.	47.2	15.3	P
46	Unidentified sandy loam	Denver, Colo.	50.0	14.1	G
47	Unidentified silt loam	Salt Lake City, Utah	51.6	16.1	P
51	Acadia clay	Spindletop, Tex.	69	49	P
52	Lake Charles clay loam	League City, Tex.	69	47	P
53	Cecil clay loam	Atlanta, Ga.	61.2	48.3	G
54	Fairmount silt loam	Cincinnati, Ohio	53.2	38.6	P
55	Hagerstown loam	Baltimore, Md.	55.4	42.6	G
56	Lake Charles clay	El Vista, Tex.	69	49	P
57	Merced clay adobe	Tranquillity, Calif.	63	8	P
58	Muck	New Orleans, La.	69.3	57.4	VP

(See footnote at end of table.)

TABLE 19.—*Test sites, soil numbers, types, locations, and other information relating to soils at NBS, AGA, and API test sites*—Continued.

[G, good; F, fair; P, poor; VP, very poor]

Soil[a]	Soil type	Location	Mean temperature[b]	Annual precipitation[b]	Internal drainage of test site
		NATIONAL BUREAU OF STANDARDS SITES			
			°F	Inches	
59	Carlisle muck	Kalamazoo, Mich.	49	31	VP
60	Rifle peat	Plymouth, Ohio	49	37	VP
61	Sharkey clay	New Orleans, La.	69.3	57.4	P
62	Susquehanna clay	Meridian, Miss.	64.0	53.0	P
63	Tidal marsh	Charleston, S. C.	66.0	45.2	VP
64	Docas clay	Cholame Flats, Calif.	58	16	VP
65	Chino silt loam	Wilmington, Calif.	62.4	15.2	F
66	Mohave fine gravelly loam	Phoenix, Ariz.	69.7	7.8	G
67	Cinders	Milwaukee, Wis.	46.1	30.1	VP
68	Gila clay	Phoenix, Ariz.	69.7	7.8	F
69	Houghton muck	Kalamazoo, Mich.	49	31	P
70	Merced silt loam	Buttonwillow, Calif.	65	6	P
71	Mahoning silt loam	Austintown Junction, Ohio	.....	.....	VP
72	Trumbull clay loam	Yale, Ohio	.....	.....	VP
76	Chino silt loam	Los Angeles, Calif.	62.4	15.2	F
77	Susquehanna clay	Meridian, Miss.	64.0	53.0	P
78	Caddo fine sandy loam	Latex, La.	64.0	53.0	VP
101	Billings silt loam (low alkali)	Grand Junction, Colo.	52.0	8.8	F
102	Billings silt loam (moderate alkali)	....do	52.0	8.8	F
103	Billings silt loam (high alkali)	....do	52.0	8.8	F
104	Cecil clay	Charlotte, N. C.	60.2	46.1	G
105	Cecil clay loam	Macon, Ga.	64.2	44.5	G
106	....do	Salisbury, N. C.	60	46	G
107	Cecil fine sandy loam	Raleigh, N. C.	60.1	46.3	G
108	Cecil gravelly loam	Atlanta, Ga.	61.2	48.3	G
109	Fresno fine sandy loam (low alkali)	Fresno, Calif.	63	9	P
110	Fresno fine sandy loam (moderate alkali)	....do	63	9	P
111	Fresno fine sandy loam (high alkali)	Kernell, Calif.	63	9	P
112	Imperial clay (moderate alkali)	Niland, Calif.	71	2	F
113	Imperial clay (high alkali)	....do	71	2	F
114	Lake Charles clay	El Vista, Tex.	69	49	P
115	Memphis silt loam	Vicksburg, Miss.	65.6	51.9	G
116	Merced clay	Los Banos, Calif.	63.4	8.1	F
117	Merced clay loam adobe	Tranquillity, Calif.	63	8	P
118	Niland gravelly sand (low alkali)	Niland, Calif.	71	2	F
119	Norfolk sandy loam	Macon, Ga.	64.2	44.5	G
120	Norfolk sand	Pensacola, Fla.	67.7	57.9	G
121	....do	Tampa, Fla.	71.8	49.4	G
122	Panoche clay loam	Mendota, Calif.	63	6.4	F
123	Susquehanna clay	Shreveport, La.	65.8	43.4	P
124	Susquehanna silt loam	Troup, Tex.	66.0	42.7	P
125	Susquehanna fine sandy loam	Shreveport, La.	65.8	43.4	P
		AMERICAN GAS ASSOCIATION SITES			
1	Cinders	Pittsburgh, Pa.	.....	.....	.....
2	....do	Milwaukee, Wis.	46.1	30.1	VP
3	Tidal marsh	Brockton, Mass.	.....	.....	P
4	....do	Atlantic City, N. J.	.....	.....	P
5	Muck	West Palm Beach, Fla.	.....	.....	P
6	....do	Miami, Fla.	.....	.....	P
7	Cecil clay loam	Atlanta, Ga.	61.2	48.3	G
8	....do	Raleigh, N. C.	60.1	46.3	G
9	Susquehanna clay	Shreveport, La.	65.8	43.4	P
10	Miller clay	....do	65.8	43.4	P
11	....do	Bryan, Tex.	.....	.....	P

(See footnote at end of table.)

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TABLE 19.—*Test sites, soil numbers, types, locations, and other information relating to soils at NBS, AGA, and API test sites*—Continued.

[G, good; F, fair: P, poor; VP, very poor]

Soil[a]	Soil type	Location	Mean temperature[b]	Annual precipitation[b]	Internal drainage of test site
		AMERICAN GAS ASSOCIATION SITES			
			°F	*Inches*	
12	White alkali soil	Los Angeles, Calif.	62.4	15.2	.....
13	Black alkali soil	....do	62.4	15.2	G
14	Marshall silt loam	Kansas City, Mo.	54.4	37.1	G
		AMERICAN PETROLEUM INSTITUTE SITES			
I	Bell clay	Temple, Tex.	.....	.....	.....
II	Oswego silt loam	Arkansas City, Kans.	.....	.....	.....
III	Lake Charles clay	Beaumont, Tex.	69	49	P
IV	Lake Charles clay loam	League City, Tex.	.....	.....	VP
V	Miami silt loam	Preble, Ind.	.....	.....	.....
VI	Not determined	Council Hill, Okla.	.....	.....	.....
VII	Oswego silt loam	Caney, Kans.	.....	.....	.....
VIII	Acadia clay	Spindle Top Gulley, Tex.	69	49	VP
IX	Hanford fine sandy loam	Lower Berea, Calif.	.....	.....	.....
X	Muscatine silt loam	Mt. Auburn, Ill.	.....	.....	.....
XI	Not determined	Skiatook, Okla.	.....	.....	.....
XII	Merced clay loam	Mendota, Calif.	63	6.4	P
XIII	Miller clay	Bunkie, La.	67	56	VP
XIV	Hagerstown silt loam	Chambersburg, Pa.	.....	.....	.....
XVI	Docas clay	Cholame, Calif.	58	16	VP

[a] Different numbers for soils that appear to be identical indicate either different sites in the same locality or that different classes of materials were buried at different times at the same site.
[b] Data furnished by United States Weather Bureau. Values with no figures to the right of the decimal point are for some nearby city.
[c] The soil types of soils 71 to 78 are subject to change upon better identification.

The selection of the test sites was governed to a large extent by the distribution of pipe lines and pipe networks, that is by the importance of the soil with respect to underground construction. Each test site represents an important soil condition, but as within an area of a few square miles several quite different soils usually exist, they are not necessarily representative of the soil conditions prevailing in the region of the site. This is illustrated by figure 7, which shows the soil series in a 6- by 7½-mile area just east of Baltimore, Md. [46].

It should be obvious that a test of materials in any one locality may not indicate the behavior of the materials in a different soil which may lie within a short distance from the test site. Moreover, as the soil horizons of a single soil may differ widely in physical and chemical properties, degree of aeration, and moisture content, a test of pipe materials in one soil horizon may yield results different from those of a test of the same materials exposed to another horizon of the same soil type. For example, the averages of the two deepest pits on five ferrous materials buried for 5 years in Rifle peat near Plymouth, Ohio, were 38, 37, 21, 24, and 67 mils, respectively. The corresponding values for the pit depths on the same materials exposed for 7 years at the same site were 30, 34, 16, 17, and 62 mils, respectively. An examination of the site showed that the two sets of specimens were placed in two paralleled trenches only a few feet apart. The depths of the trenches were approximately the same, but the 5-year-old specimens were laid in the peat horizon, whereas the 7-year-old specimens were placed in the clay subsoil just below the peat. The surface of the ground was level, but the thickness of the peat layer varied.

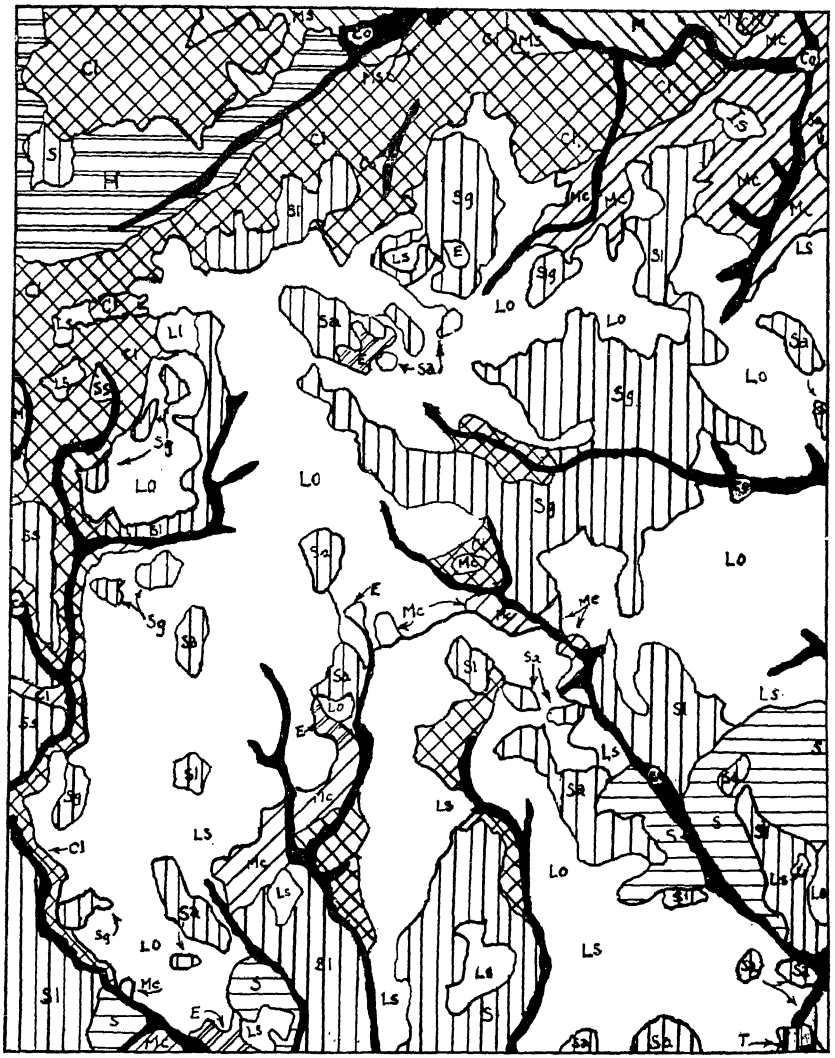

FIGURE 7.—*Soil series in a 6- by 7½-mile area near Baltimore, Md.*

Cl	= Chester loam.	Mc	= Montalto clay loam.
Co	= Congaree silt loam.	S	= Susquehanna silt loam.
E	= Elkton silt loam.	Sa	= Sassafras sandy loam.
H	= Hagerstown loam.	Sg	= Sassafras gravelly loam.
Is	= Iredell silt loam.	Sl	= Sassafras loam.
Lo	= Leonardstown loam.	Ss	= Sassafras silt loam.
Ls	= Leonardstown silt loam.	T	= Tidal Marsh.
M	= Manor loam.		

For convenience, the descriptions of the soils at the Bureau sites have been arranged according to the arbitrarily assigned numbers of the test sites. Those who are interested in the classifying of the soils as to the great soil groups to which they belong should refer to table 1.

Tables 20 to 23 show the more important properties of the soils to which specimens were exposed. Since these data were obtained, it has been discovered that the pH of some poorly drained and poorly aerated soils changed after they were exposed to air [47]. As the soils were

air-dried and pulverized before the analyses given in table 20 were made, it is probable that the pH values given for some of the soils are incorrect. New values will be obtained as soon as conditions permit.

TABLE 20.—*Chemical properties*[a] *of soils at National Bureau of Standards test sites.*
[A, Alkaline; C, not determined.]

Soil[b] No.	pH	Total acidity, mg-eq per 100 g of soil	Resistivity at 60° F	Composition of water extract, mg-eq per 100 g of soil						
				Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4
			Ohm-cm							
1	7.0	11.4	1,215	0.72	0.25	0.43	0.00	0.09	0.09	0.83
2	7.3	3.5	684	.28	1.09	.13	.00	1.18	.04	.18
3	5.2	11.5	30,000	.....	.....	.....	.....	.....	.....	.....
4	5.6	7.6	6,670	.....	.....	.....	.....	.....	.....	.....
5	7.0	6.5	1,346	.93	0.48	.10	.00	0.69	.03	.25
6	5.9	12.8	45,100	.....	.....	.....	.....	.....	.....	.....
7	4.4	29.8	2,120	.....	.....	.....	.....	.....	.....	.....
8	7.6	A	350	1.42	1.72	2.55	.00	.71	.01	4.43
9	6.8	7.2	2,820	.....	.....	.....	.....	.....	.....	.....
10	6.6	3.6	7,460	.....	.....	.....	.....	.....	.....	.....
11	5.3	10.8	11,000	.....	.....	.....	.....	.....	.....	.....
12	7.1	2.5	3,190	0.39	0.50	0.16	.00	.40	.00	0.14
13	9.5	A	290	6.23	.09	.13	.00	1.12	1.64	3.76
14	6.2	5.6	3,520	.....	.....	.....	.....	.....	.....	.....
15	7.5	5.0	489	2.18	.88	.20	.00	2.00	0.13	0.73
16	4.4	11.8	8,290	.....	.....	.....	.....	.....	.....	.....
17	4.5	19.1	5,980	.....	.....	.....	.....	.....	.....	.....
18	7.3	1.4	1,410	0.27	.63	.20	.00	.94	.00	.25
19	4.6	10.9	1,970	.38	.32	.41	.00	.16	.03	.46
20	7.5	1.5	2,870	.25	.48	.20	.00	.51	.00	.15
21	6.2	9.5	2,370	.....	.....	.....	.....	.....	.....	.....
22	4.9	9.7	5,150	.....	.....	.....	.....	.....	.....	.....
23	9.4	A	278	8.38	.38	.22	.02	1.87	1.12	5.57
24	4.5	12.6	11,400	.....	.....	.....	.....	.....	.....	.....
25	7.2	4.7	1,780	0.23	.70	.41	.00	1.01	0.03	0.10
26	7.3	2.6	2,980	.27	.50	.31	.00	0.70	.03	.12
27	6.6	3.7	570	.53	1.86	1.12	.00	2.00	.08	1.54
28	6.8	C	408	1.50	0.06	0.18	.00	0.12	.99	0.89
29	4.2	28.1	1,270	2.15	1.92	1.55	.00	.00	1.69	2.30
30	7.0	2.6	1,300	0.32	0.65	0.40	.00	.71	0.09	0.24
31	4.7	1.8	20,500	.....	.....	.....	.....	.....	.....	.....
32	7.3	0.5	5,700	.23	.70	.12	.00	.73	.01	.42
33	6.8	36.0	800	1.52	7.30	4.06	.00	C	2.27	2.13
34	6.7	7.0	4,900	.....	.....	.....	.....	.....	.....	.....
35	7.3	5.7	2,060	0.68	0.68	0.49	.00	1.10	0.06	0.35
36	4.5	4.6	11,200	.....	.....	.....	.....	.....	.....	.....
37	3.8	15.3	11,200	.....	.....	.....	.....	.....	.....	.....
38	4.5	1.7	38,600	.....	.....	.....	.....	.....	.....	.....
39	5.6	6.6	7,440	.....	.....	.....	.....	.....	.....	.....
40	6.0	9.4	970	0.56	0.58	0.44	.00	0.93	.07	.28
41	5.5	11.0	1,320	.30	.54	.36	.00	.78	.04	.46
42	4.7	28.2	13,700	.....	.....	.....	.....	.....	.....	.....
43	3.1	36.8	60	45.10	5.17	9.45	.00	.00	43.30	37.00
44	5.8	8.8	1,000	1.05	1.08	0.66	.00	1.97	0.82	0.41
45	7.4	A	263	8.15	3.70	.70	.00	0.24	.18	11.98
46	7.0	C	1,500	.....	.....	.....	.....	.....	.....	.....
47	7.6	3.0	1,770	0.67	0.72	.39	.00	.88	.06	0.48
51	6.2	13.2	190	10.27	15.55	5.03	.00	.56	5.75	22.00
52	8.8	A	234	4.20	.33	.18	.52	1.36	1.33	1.26
53	4.6	9.6	17,794	.....	.....	.....	.....	.....	.....	.....
54	7.0	3.5	886	0.59	10.10	0.59	.00	.70	0.08	9.05
55	5.8	10.9	5,213	.....	.....	.....	.....	.....	.....	.....
56	7.1	4.5	406	3.12	0.69	.47	.00	.80	1.59	3.04
57	7.7	A	128	23.40	13.50	4.51	.00	.34	1.15	37.50
58	4.0	79.3	712	2.03	2.23	1.29	.00	.00	0.47	2.54
59	5.5	33.3	1,659	1.03	3.08	2.70	.00	.00	3.47	1.04
60	2.6	297.4	218	2.91	10.95	2.86	.00	.00	0.00	56.70
61	5.9	8.6	943	0.73	0.68	0.33	.00	.71	.10	0.91
62	4.1	24.2	6,922	.....	.....	.....	.....	.....	.....	.....
63	2.9	100.2	84	33.60	6.85	4.00	.00	.00	12.70	36.00
64	8.3	A	62	28.10	2.29	0.76	.00	.89	28.80	0.26
65	7.2	A	148	7.65	12.40	2.20	.00	1.30	6.05	16.90
66	8.7	A	232	6.55	0.51	0.18	.00	0.73	2.77	2.97
67	8.0	A	455	0.77	3.03	.53	.00	.55	0.08	2.89
68	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

(See footnote at end of table.)

TABLE 20.—*Chemical properties*[a] *of soils at National Bureau of Standards test sites*—Continued.

[A, Alkaline; C, not determined.]

Soil[b] No.	pH	Total acidity, mg-eq per 100 g of soil	Resistivity at 60° F	Composition of water extract, mg-eq per 100 g of soil						
				Na+K as Na	Ca	Mg	CO_3	HCO_3	Cl	SO_4
			Ohm-cm							
69	5.5	33.3	1,659	1.03	3.08	2.70	.00	.00	3.47	1.04
70	9.4	A	278	8.38	0.38	0.22	.02	1.87	1.12	5.57
71	...	...	...	...	...	...	...	...	...	...
72	7.2	...	762	...	...	...	...	...	...	...
73	...	...	...	...	...	...	...	...	...	...
74	...	...	...	...	...	...	...	...	...	...
75	...	...	...	...	...	...	...	...	...	...
76	...	...	...	...	...	...	...	...	...	...
77	...	...	...	...	...	...	...	...	...	...
78	...	...	...	...	...	...	...	...	...	...
101	7.3	A	261	5.21	19.24	1.43	.00	0.66	1.56	22.48
102	7.3	A	103	22.63	16.56	3.85	.00	.56	4.67	36.82
103	7.3	A	81	22.01	13.32	2.00	.00	.18	11.09	25.70
104	4.6	11.0	8,500	...	...	...	...	...	...	...
105	4.8	12.9	28,000	...	...	...	...	...	...	...
106	4.8	12.8	25,000	...	...	...	...	...	...	...
107	4.8	11.8	54,400	...	...	...	...	...	...	...
108	4.9	11.2	44,400	...	...	...	...	...	...	...
109	8.4	A	497	2.62	0.07	0.10	.31	.59	1.56	0.48
110	10.2	A	531	3.53	.07	.12	1.49	1.07	0.79	.25
111	7.3	A	51	41.55	16.21	.44	0.00	0.58	34.58	23.41
112	7.4	A	149	22.18	14.09	1.29	.00	.36	10.94	25.98
113	7.4	A	102	9.56	0.84	.51	.00	.63	6.26	4.06
114	7.1	C	320	2.65	0.68	0.26	.00	.77	1.84	0.93
115	6.9	4.7	3,450	...	...	...	...	...	...	...
116	9.2	A	320	9.30	.33	.18	4.60	2.10	1.17	1.57
117	8.5	A	106	36.19	14.66	.83	0.00	1.55	2.89	46.53
118	7.3	A	273	4.30	1.03	.64	.00	0.20	5.01	0.86
119	4.7	9.7	10,800	...	...	...	...	...	...	...
120	5.7	1.3	34,400	...	...	...	...	...	...	...
121	4.8	1.2	16,400	...	...	...	...	...	...	...
122	7.4	A	552	2.32	0.05	.26	.00	.70	0.07	1.40
123	4.1	21.9	6,840	...	...	...	...	...	...	...
124	4.4	28.1	1,160	...	...	...	...	...	...	...
125	3.9	28.3	5,770	...	...	...	...	...	...	...

[a] Measurements and determinations by I. A. Dension and R. B. Hobbs.
[b] See table 19 for names and locations of soils.

Soil[b] No.	Moisture equivalent	Airpore space	Apparent specific gravity	Volume shrinkage
	%	%		%
1	28.6	1.1	.....	6.6
2	37.6	2.0	1.95	23.0
3	29.1	18.2	1.60	7.0
4	22.2	7.0	1.78	2.2
5	28.8	4.9	2.00	22.6
6	12.2	40.6	1.50	0.1
7	34.3	3.7	2.02	31.5
8	37.0	8.7	1.56	21.0
9	24.8	15.8	1.74	5.6
10	13.0	27.8	1.58	0.2
11	32.0	15.5	1.49	8.6
12	12.4	33.5	.....	0
13	21.7	34.5	.....	0
14	17.2	14.4	1.76	1.0
15	51.4	5.7	2.08	39.8
16	22.2	12.0	1.65	.6
17	30.8	4.4	1.72	5.4
18	28.4	15.6	1.26	1.3
19	28.4	3.9	1.76	11.8
20	22.4	3.8	1.90	3.9
21	31.2	10.8	1.66	6.5
22	28.4	9.6	1.67	3.0
23	21.7	6.1	1.69	0.2
24	13.0	34.7	1.4	0
25	25.8	9.5	1.95	7.6
26	16.4	20.9	1.95	1.0
27	42.6	1.9	2.01	32.5
28	24.6	2.5	.....	5.9
29	34.5	26.6	.....	5.8
30	29.4	7.2	1.81	7.5
31	2.8	38.1	1.55	0
32	17.8	11.7	1.85	0.1
33	72.8	34.0	.....	16.9
34	23.4	11.7	1.82	8.4
35	18.0	10.9	1.89	3.1
36	13.8	16.0	1.62	0
37	7.0	.....	.....	0
38	3.0	32.1	1.59	0
39	21.2	7.5	1.72	3.8
40	33.0	2.3	1.78	16.4
41	33.1	6.9	1.61	14.6
42	34.8	14.9	1.79	4.7
43	55.4	.....	.....	.....
44	31.2	7.2	1.55	6.0
45	14.8	18.7	.....	0
46	7.6	23.2	.....	0
47	25.7	2.6	1.72	3.7
51	47.1	1.4	2.07	37.9
52	51.8	3.7	[c]1.97	33.9
53	33.7	18.2	1.60	7.0
54	26.1	4.7	1.96	6.1
55	32.0	15.5	1.49	8.6
56	28.7	5.0	2.03	30.1
57	40.9	5.1	1.89	29.5
58	57.8	22.4	1.43	36.9
59	43.6	.....	.....	.....
60	43.4	33.2	1.28	9.1
61	30.8	2.3	1.78	16.4
62	34.6	11.9	1.79	4.7
63	46.7	19.5	1.47	18.8
64	41.1	4.7	1.88	27.7
65	26.4	15.8	1.41	5.7
66	16.5	20.1	1.79	2.7
67	11.1	.....	.....	.....
68	.....	.....	.....	.....
69	43.6	.....	.....	.....
70	24.7	6.1	1.69	0.2
71	.....	.....	.....	.....
72	.....	.....	.....	.....
73	.....	.....	.....	.....
74	.....	.....	.....	.....
75	.....	.....	.....	.....
76	.....	.....	.....	.....
77	.....	.....	.....	.....
78	.....	.....	.....	.....
101	30.0	.....	.....	.....
102	20.4	.....	.....	.....
103	30.6	.....	.....	.....
104	34.1	.....	.....	.....
105	34.2	.....	.....	.....
106	38.8	.....	.....	.....
107	29.6	.....	.....	.....
108	31.3	.....	.....	.....
109	18.6	.....	.....	.....
110	18.4	.....	.....	.....
111	22.1	.....	.....	.....
112	31.6	.....	.....	.....
113	30.2	.....	.....	.....
114	35.8	.....	.....	.....
115	25.7	.....	.....	.....
116	39.7	.....	.....	.....
117	51.8	.....	.....	.....
118	6.1	.....	.....	.....
119	24.1	.....	.....	.....
120	4.4	.....	.....	.....
121	3.0	.....	.....	.....
122	30.0	.....	.....	.....
123	37.6	.....	.....	.....
124	36.0	.....	.....	.....
125	37.2	.....	.....	.....

[a] Measurements and determinations by I. A. Denison and R. B. Hobbs.
[b] See table 19 for names and locations of soils.
[c] Measurement made on 20-mesh soil after centrifuging.

Soil[b] No.	Depth	Mechanical analysis				Suspension percentage
		Sand	Silt	Clay	Colloid	
	Inches	%	%	%	%	%
1	90	9.8	37.7	52.5	31.1	38.0
2	40	17.2	37.9	44.9	40.4	19.1
3	32	29.0	24.9	46.1	37.8	4.4
4	36	29.3	53.0	17.7	9.9	27.9
5	30	25.6	38.6	35.8	30.2	40.8
6	36	69.0	23.8	7.2	3.5	12.2
7	40	10.3	26.1	63.6	55.0	41.2
8	48	2.2	27.7	70.1	50.7	20.2
10	30	64.0	29.4	6.6	2.8	16.4
11	60	25.8	21.1	53.1	45.9	7.9
14	60	56.6	29.5	13.9	9.5	19.8
15	36	4.4	25.2	70.4	62.0	28.3
16	30	50.4	23.1	26.5	21.8	11.1
17	36	9.6	38.6	51.7	39.6	43.5
18	48	1.3	78.4	20.3	15.0	24.2
19	36	15.7	50.1	34.2	29.3	15.9
20	50	19.6	44.1	36.3	23.7	37.7
21	36	3.2	65.9	30.9	27.1	26.0
22	33	1.2	76.5	22.3	18.3	38.7
24	33	72.0	22.4	5.6	2.7	10.4
25	36	21.0	43.0	36.0	21.8	24.8
27	30	1.4	10.8	87.8	71.5	30.2
30	36	2.1	65.5	32.4	26.1	25.7
31	24	97.3	2.1	0.6	.....	1.8
32	48	42.1	42.1	15.8	8.2	15.9
35	36	35.9	37.3	26.0	19.3	22.2
36	36	60.6	21.8	17.6	14.8	17.0
37	30	90.6	4.9	4.5	4.3	3.3
39	36	42.1	42.6	15.3	8.7	18.9
40	30	2.5	50.4	47.1	32.8	24.9
41	36	3.0	56.7	40.3	35.0	24.7
42	30	30.1	24.1	45.8	40.9	11.8
44	30	2.4	66.4	31.2	25.8	22.1
47	36	9.0	44.9	46.1	27.7	45.5

[a] Measurements and determinations by I. A. Denison and R. B. Hobbs
[b] See table 19 for names and locations of soils.

TABLE 21.—*Physical Properties*[a] *of soils at National Bureau of Standards test sites.*

TABLE 23.—*Properties of the soils in the American Gas Association and American Petroleum Institute coating tests.*

Soil No.	Soil type	Moisture equivalent	Volume shrinkage	Air-pore space	Apparent specific gravity	pH (average)	Total acidity (mg-eq per 100 g of soil)	Resistivity, at 60° F
	AMERICAN GAS ASSOCIATION TEST SITES							
		%	%	%				*Ohm-cm*
1	Cinders	18.2	.....	.....	.....	5.5	.....	730
2	....do	9.5	.....	.....	.....	7.2	.....	380
3	Tidal marsh	50.3	.....	.....	.....	3.6	42.5	44
4	...do	93.7	.....	.....	.....	3.0	38.0	32
5	Muck	74.2	15.0	.....	.....	4.3	75.8	1,180
6	....do	29.1	.....	.....	.....	5.7	22.2	1,650
7	Cecil clay loam	35.0	40.4	.....	.....	5.8	13.3	43,800
8	....do	37.6	38.8	.....	.....	6.9	6.3	16,000
9	Susquehanna clay	35.8	35.5	.....	.....	4.6	15.7	6,840
10	Miller clay	32.0	37.2	.....	.....	7.4	1.1	870
11	....do	47.8	49.9	.....	.....	7.2	0	1,000
12	White alkali soil	35.6	45.0	.....	.....	7.3	.....	93
13	Black alkali soil	16.6	14.0	.....	.....	9.2	.....	1,700
14	Marshall silt loam	31.0	41.0	.....	.....	6.5	12.8	3,150
	AMERICAN PETROLEUM INSTITUTE TEST SITES							
I.	Bell clay	31.6	28.0	5.1	2.00	8.4		947
II.	Oswego silt loam	20.7	5.1	19.2	1.76	7.0		1,295
III.	Lake Charles clay	40.7	35.8	2.6	2.00	6.8		495
IV.	Lake Charles clay loam	21.1	6.7	5.1	1.93	7.2		1,485
V.	Miami silt loam	21.5	6.4	6.9	1.87	6.3		2,201
VI.	Unidentified	25.4	11.6	5.5	1.78			5,180
VII.	Oswego silt loam	20.6	7.0	13.8	2.04	5.4		3,510
VIII.	Acadia clay	47.6	42.7	2.9	2.04	5.4		259
IX.	Hanford fine sandy loam	9.8	0	29.9	1.47	8.9		353
X.	Muscatine silt loam			.....	.....	6.+		
XI.	Unidentified	15.7	0	16.6	1.65	5.2		440
XII.	Merced clay loam	36.8	31.2	7.2	1.84	8.9		61
XIII.	Miller clay	38.0	30.2	2.5	2.01	7.9		674
XIV.	Hagerstown silt loam	21.3	1.4	8.3	1.46	6.4		5,088
XVI.	Docas clay	36.8	29.1	3.8	1.88	8.4		155

4. FACTORS AFFECTING RESULTS OF CORROSION TESTS

Among the factors that affect the results of corrosion tests are depth of burial, mill and foundry scale, diameter of the pipe, area of pipe surface, and duration of exposure. In order to gain an idea of the nature and relative magnitudes of the influence of these factors, several supplementary tests were carried out.

(a) DEPTH OF BURIAL

In general, aeration in soils will decrease as the distance below the surface increases and, therefore, the corrosivity of the soil should be expected to increase with depth. In fact, pipe-line operators have often reported more severe corrosion where their lines are deeper than usual. In order to investigate the effect of depth of burial, samples of 3-inch steel pipe were buried at different depths in seven soils having different general characteristics. The results of this series of tests are given in Table 24. In five of the seven soils, the amount of corrosion was greater at the greater depths. In two of the soils, however, the reverse was true. This is probably due to the counteracting effect of the subsoils. For instance, in the case of St. John's sand (soil 37), in which corrosion was greater near the surface there is an impervious hardpan layer about 6

inches thick at about 18 inches below the surface of the ground. If pipes are laid in or above this layer, they may be surrounded by water much of the time because the water can not get through the layer. If pipes are laid deeper, they will be placed in sand, which will let the water pass more readily. In the arid regions of the West, the concentration of the alkali may be either near the surface or at a considerable depth, depending on the prevailing direction of the movement of moisture in the soil. Thus it can be seen that, although corrosion in general increases with depth of burial, other influences, such as drainage and the characteristics of soil horizons, may be sufficient to mask completely the effect of depth.

TABLE 24.—*Effect of depth of burial on corrosion of 3-inch steel pipe.*

[Average of four specimens]

Soil number	Type of soil	Depth of burial	Loss of weight	Maximum penetration
	EXPOSURE OF 11.70 YEARS			
		in.	*oz/ft²*	*Mils*
37	St. John's fine sand	12	10.13	67
37	....do	24	9.05	64
37	....do	36	5.27	50
37	....do	48	4.71	44
	EXPOSURE OF 9.27 YEARS			
103	Billings silt loam (high alkali)	14	16.33	118
103	....do	22	17.99	136
103	....do	28	17.66	143
103	....do	48	20.76	172
	EXPOSURE 11.71 YEARS			
104	Cecil clay	18	5.61	80
104	....do	30	8.18	102
104	....do	36	9.07	110
104	....do	52	7.92	166
	EXPOSURE 11.70 YEARS			
107	Cecil fine sandy loam	12	3.89	53
107	....do	24	4.40	64
107	....do	36	4.85	89
	EXPOSURE 9.24 YEARS			
110	Fresno fine sandy loam	19	13.96	113
110	....do	26	18.18	124
110	....do	42	18.63	159
	EXPOSURE 5.93 YEARS			
113	Imperial clay (high alkali)	12	17.90	166
113	....do	22	20.05	211
113	....do	28	21.66	212
113	....do	40	21.69	198
	EXPOSURE 9.27 YEARS			
117	Merced clay adobe	12	20.28	127
117	....do	24	19.09	122
117	....do	36	19.70	87
117	....do	48	12.03	83

(b) MILL AND FOUNDRY SCALE

The oxide which forms on the surface of a pipe as the result of rolling or casting is at a more noble potential than that of the unoxidized metal, and the oxide probably corrodes more slowly. Indeed, the corrosion-resisting properties of stainless steel are attributed to a very thin oxide film which reforms whenever it is removed. A continuous oxide film should retard or prevent corrosion. However, if unoxidized metal is exposed adjacent to the oxide, a difference of potential is created which tends to accelerate the corrosion of the unoxidized metal. Unfortunately, the oxide scale on a pipe is seldom continuous. In 1926, specimens of several materials in their original condition and similar materials with the mill scale removed were buried in seven soils. Table 25 shows the rates of corrosion of these specimens after approximately 8 years of exposure [45]. To facilitate the comparison of the materials with and without mill scale, the ratio of the number of cases in which the scale-free material was superior to the scale-coated specimens is given at the bottom of each part of the table. It is evident from the table that the majority of the specimens from which the scale had been removed corroded somewhat less than those having a coating of mill scale, that is, mill and foundry scale did not afford any protection to the specimens. However, the improvement is too slight to warrant the removal of mill scale.

TABLE 25.—*Effect of mill and foundry scale on corrosion.*

[Period of exposure was approximately 8 years]

Soil	Soil type	Pit cast iron		deLavaud cast iron		Steel		Wrought iron	
		Normal, A	Machined MC	Normal, C	Machined, MD	Normal, P	Ground and polished, M	Normal, K	Rough ground, D
	RATE OF LOSS OF WEIGHT (oz/ft²)/yr								
13	Hanford very fine sandy loam	1.12	1.29	0.05	1.10	1.70	1.51	1.12	1.01
24	Merrimac gravelly sandy loam	0.11	0.13	.17	0.16	.....	.....	0.22	0.18
28	Montezuma clay adobe	3.94	.....	1.14	.....	.....	.....	.....	.....
29	Muck	2.31	0.99	5.28	1.27	1.21	1.06	1.18	1.22
42	Susquehanna clay	0.70	0.43	0.59	0.47	0.89	0.94	0.88	0.80
43	Tidal marsh	1.08	1.00	3.08	1.20	.86	1.14	.67	.67
45	Unidentified alkali	3.50	.....	3.55	2.59	2.64	2.26	2.51	2.17
	Ratio[a]	.....	3:5	.....	5:6	.....	3:5	.....	4:6
	RATE OF PENETRATION (mils/yr)								
13		17.8	12.8	7.8	9.1	19.3	15.3	11.9	11.1
24		3.6	3.2	3.8	2.4	.....	.....	4.7	3.8
28		20.4	.....	6.8	.....	.....	.....	.....	.....
29		11.4	5.0	10.7	8.9	10.5	9.8	6.3	7.3
42		17.9	15.9	7.0	8.9	8.8	10.0	10.3	9.4
43		14.1	5.2	27.5	11.5	10.8	8.1	15.3	9.7
45		22.3	.....	14.3	15.7	16.6	13.0	12.9	18.2
	Ratio[a]	.....	5:5	.....	3:6	.....	4:5	.....	4:6

[a] Ratio of cases of superiority to total number of cases of comparison.

(c) DIAMETER OF PIPE

When tests of small sections of pipes are planned, the question of the effect of the diameter of the pipe may arise. If the diameter of the pipe

is so large that the pipe lies in two soil horizons, or if only part of it is under water, or if there is a considerable difference in the distances from the surface of the ground to the top and bottom of the pipe, differential aeration circuits will be set up which will affect the distribution of the corrosion on the surfaces of the pipe and possibly the amount of corrosion also. It is not often, however, that such large diameter pipes are used in corrosion tests.

Table 26 shows the effect of diameter on the depths of the maximum pits on two different materials as calculated in three different ways. From each soil there were removed one specimen of 6-inch cast-iron pipe, two specimens of 3-inch cast iron, and two specimens of 3-inch steel pipe, all 6 inches long. There were also removed from each soil two specimens of cast iron 12 inches long with external diameters of approximately 1.9 inches, and two 10-inch lengths of 2-inch open-hearth steel. By treating the two specimens of each material, except the 6-inch cast iron, as a single specimen having twice the area of one, it is possible to compare the pit depths on specimens of different materials and diameters having approximately the same areas. Columns 1 to 5 of table 26 permit such a comparison.

TABLE 26.—*Average of maximum pit depth on pipes of different diameters for four periods of exposure.*

Soil number	Single maximum pit					Average of two deepest pits					Weighted[b] maximum pit depths of cast iron		
	Cast iron			Steel		Cast iron			Steel				
	6 in.	3 in.	1¼ in.	3 in.	2 in.	6 in.	3 in.	1¼ in.	3 in.	2 in.	6 in.	3 in.	1¼ in.
	1	2	3	4	5	6	7	8	9	10	11	12	13
	Mils	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*
[a]51	169	151	[b]212+	60	136+	155	128	206+	52	124+	145	101	201+
53	68	72	61	58	53	63	58	55	55	50	54	49	52
55	37	48	93	69	60	33	42	87	64	55	31	38	82
56	139	147	166+	156+	106+	125	133	166+	150+	95+	111	123	160+
58	129	125	195+	70	97	124	113	194+	69	75	114	105	134+
[a]59	50	43	58	39	39	47	37	35	35	25	43	36	91+
60	[c]105*s*	111	102+	114+	36	100*s*	100	81+	88+	27	89*s*	96	63+
61	60	67	74	56	76	54	58	68	50	63	49	54	58
62	82	79	103	70	85	77	71	92	58	74	75	65	75
63	43	42	81	134+	51	38	38	69	98+	44	32	34	66
64	225	195	163+	178+	150+	216	187	155+	160	148+	197	195	137+
65	140	162	123	120+	83	132	143	101	102+	79	121	129	96
66	168	167	146+	171	133+	157	164	119+	154	132+	143	150	103
67	141*s*	164	231+	139*s*	154+	122*s*	142	217+	112	147+	110*s*	118	200+
Average	111	112	129	102	90	103	101	118	89	81	94	92	108

[a] Average for 3 periods of exposure only.
[b] A plus (+) sign indicates that 1 or both removals were punctured during 1 or more periods.
[c] *s* indicates that uniform corrosion occurred on 1 or more specimens.

In 7 of the 14 soils shown in table 26, the 6-inch cast-iron specimens developed shallower maximum pits than were observed on equal areas of 3-inch or 1¼-inch cast specimens, and the average of the maximum pits on the 6-inch specimens is less than the averages for either of the other two sizes of cast-iron pipes. The 3-inch cast specimens developed shallower maximum pits than were found on the 1¼-inch cast specimens in 6 of the 14 soils, and the average of the maximum pits in the 14 soils is slightly greater for the 1¼-inch cast iron. The 3-inch steel specimens

developed shallower maximum pits than were observed on the 2-inch steel specimens in 5 of the 13 soils for which comparisons are possible. A comparison of specimens of different diameters on the basis of the averages of the two deepest pits yield similar results (columns 6 to 10).

In earlier reports, the pit depths were weighted to take account of the difference in the areas of the specimens. The depths of the four deepest pits were averaged to obtain the recorded maximum pit depths on the 6-inch cast-iron specimens, whereas the depths of the two deepest pits on each of two 3-inch specimens were averaged to obtain the recorded maximum pit depth on the 3-inch specimens. The 1937 data [48] were treated in this way to obtain the values in columns 11, 12, and 13 of table 26. In six soils the 6-inch specimens showed deeper weighted maximum pit depths than the 3-inch cast-iron specimens, whereas in six other soils the weighted maximum pit depths on the 6-inch specimens were shallower. The averages of the weighted maximum pit depths for the 3 sizes of cast pipe in 13 soils differ by only 5 mils. It appears, therefore, that for small-diameter pipe, when the areas of the specimens are the same, the diameter has practically no effect on pit depth.

(d) AREA OF PIPE SURFACE

Early in the course of the soil-corrosion investigation it was observed that there was a tendency for the specimens 3 inches in diameter to contain deeper pits than specimens of similar materials 1½ inches in diameter. This is illustrated in table 27, which permits a comparison of the maximum pit depths on areas of 66 and 126 square inches of pipe surfaces for two metals exposed for approximately 12 years in 38 soils. As the specimens differed in diameter, as well as in area, it is possible that the difference in pit depths is affected by differences in curvature of the specimens. However, according to Shepard [49] the greater curvature of the smaller specimens should tend to concentrate the corrosion and consequently intensify the pitting on the smaller area.

The apparent effect of area seems to be different for different soils and to be slightly different for the two materials. Data, as well as theoretical considerations, indicate that the pit-depth-area relation is influenced by soil characteristics, although just what the characteristics are has not been determined. Sufficient data are not available to determine whether or not the relation is the same for all ferrous materials, but data on pitting factors suggest that the corrosion of wrought iron is somewhat more uniform and that of pit-cast iron somewhat less uniform than that of steel. The difference, however, if any exists, is not great.

The observed values of maximum pit depths obtained from measurements made on a 12-inch oil line in Miller clay [35] are shown in table 28 as a function of the area inspected. In this table are tabulated the depths of the deepest pits on each of a number of 20-foot lengths of pipe and also the averages for the depths of the deepest pits on each foot of the corresponding lengths. The data for individual lengths are given in order to show how much pit depths may vary in a single type of soil. It will be noted that the deepest pit on 48 lengths of pipe, 950 feet, was 306 mils; the average for depths of the deepest pit on each length of pipe, 20 feet, 208 mils, and the average of the deepest pits on each foot of pipe, 126 mils.

TABLE 27.—*Effect of area inspected on the observed maximum pit depths on National Bureau of Standards specimens.*

[Pit depths in mils.]

Soil No.	Depth of maximum pit				Soil No.	Depth of maximum pit			
	Bessemer steel		Wrought iron			Bessemer steel		Wrought iron	
Area	[a]66 in.²	[b]126 in.²	66 in.²	126 in.²	Area	66 in.²	126 in.²	66 in.²	126 in.²
1	119	101	81	83	27	73	83	52	59
3	71	72	90	96	30	61	69	52	56
4	85	84	88	93	31	36	45	31	46
5	49	55	52	46	32	48	70	47	67
6	19	40	22	38	33	92	103	108	111
7	46	65	43	48	34	42	60	42	66
8	77	119	103	84	35	28	90	42	59
9	36	50	46	47	36	54	47	49	50
10	43	60	54	52	37	79	99	73	82
12	57	72	58	91	38	37	52	44	29
15	58	85	61	83	39	53	113	58	74
16	61	69	67	60	40	73	83	71	70
17	42	47	40	42	41	87	80	127	89
18	44	50	48	43	42	131	97	95	98
19	78	61	71	79	43	108	90	80	173
20	78	56	52	51	44	63	99	58	73
22	71	71	66	60	45	113	137	106	92
24	25	31	25	29	46	75	136	72	80
26	48	39	47	45	47	30	29	59	38
					Average for 38 soils	63	74	63	68

[a] Specimens 1½ in. in diameter.
[b] Specimens 3 in. in diameter.

TABLE 28.—*Relation between area inspected and the observed depth of the deepest pit.*

Pipe section number	Maximum pit depth on each length[a]	Average pit depth for 1-ft. lengths	Pipe section number	Maximum pit depth on each length[a]	Average pit depth for 1-ft lengths
	Mils	*Mils*		*Mils*	*Mils*
1	176	90.8	25	287	180.0
2	126	58.6	26	185	101.2
3	183	125.0	27	122	65.7
4	205	126.2	28	290	154.7
5	208	136.7	29	258	126.3
6	202	116.7	30	160	94.5
7	227	122.0	31	125	67.9
8	174	138.3	32	258	144.4
9	207	144.3	33	233	138.5
10	217	105.3	34	190	115.9
11	137	79.6	35	188	115.8
12	257	159.3	36	207	127.4
13	[b]306	169.7	37	253	154.6
14	202	149.9	38	253	130.6
15	216	158.6	39	154	94.9
16	187	139.8	40	251	97.6
17	179	91.3	41	274	133.7
18	195	127.9	42	185	121.1
19	200	140.3	43	192	138.0
20	195	143.2	44	164	95.5
21	206	127.7	45	195	123.4
22	245	147.9	46	195	141.0
23	247	152.4	47	237	142.8
24	240	161.1	48	212	138.2
			Average	208	126

[a] Approximately 20 ft of 12-in. pipe, area 67 ft². [b] Deepest pit on 950 ft of pipe.

The relation between the average of the depths of the deepest pits on unit areas and the size of that unit is illustrated in figure 8. The data

for this figure are measurements of the deepest pit on each 20-foot length of 15 miles of a 10-inch pipe line traversing a sandy-loam soil. From these data it was possible to determine the maximum pit depth on areas corresponding to any number of lengths of pipe up to the length of the line.

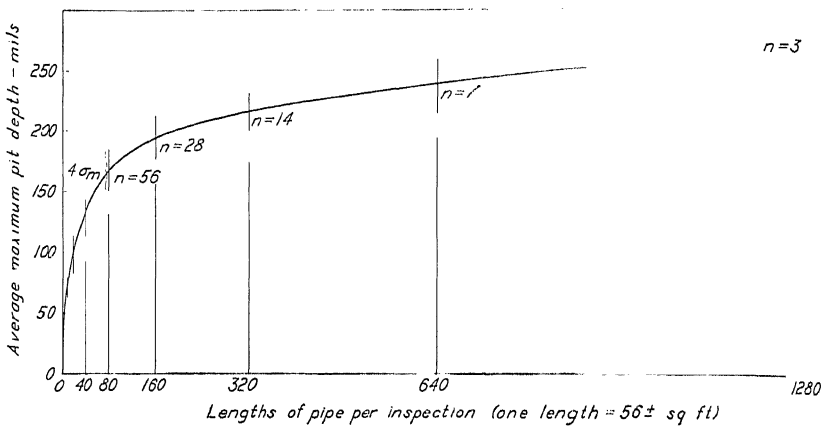

FIGURE 8.—*Relation of maximum depth of pits to area inspected.*

n = number of inspections. The short vertical lines, 4 σ_m, indicates the probable range of variations in the data.

The lengths of the vertical lines crossing the curve represent four times the standard error of the average of the maximum pit depths. The numbers on the line show the number of observations upon which the average was based. If the pit-depth-area relation were determined for a line traversing more than one soil, the data would obviously be affected by the variety of soils traversed.

Scott [50], after an extensive examination of the Bureau's soil-corrosion data and of the measurements of pits on areas up to 10,000 square feet on oil and gas lines, found that the relation between the maximum pit depth and the area from which it was selected could be represented approximately by the equation $P = bA^a$, in which P is the maximum pit depth associated with an area, A, and a and b are constants which differ for different conditions.

From an unpublished study of data from eight National Bureau of Standards test sites and from seven sets of pipe-line data, Ewing found that on the average, the equation $P = P_1\ (C \log A + 1)$, in which P is the maximum pit depth associated with an area A, P_1 the maximum pit depth on a unit area, and C is a constant varying with conditions, fitted the data better than did Scott's equation.

The fact that buried metal does not corrode uniformly can be accounted for by assuming that conditions over the surface of the metal are not uniform. This condition may be the result of lack of uniformity in the metal, differences in the soil in contact with the metal at different points, or differences in aeration resulting from the way the soil was placed over the surface of the metal. An explanation of the pit-depth-area phenomenon applicable only to small isolated specimens differing in area, is as follows: If a difference of potential exists between two areas on the surface of a specimen, the current which flows between these areas when the circuit is completed through an electrolyte is influ-

enced by the area of the cathode because of its effect on the resistance of the circuit and because of its effect on polarization. The longer the specimen, the larger will be the possible area of the cathode. However, there are few data that show definitely what is the area of the cathode associated with a single pit.

If the explanations that have been given fully account for the pit-depth-area relation, it might be expected that when the maximum pit depths on a number of specimens having large areas are averaged, some area would be found such that larger areas would not contain deeper pits.

Figure 8 suggests that such may not be the case, as the maximum pit appears to increase in depth with increase in the area chosen for the unit of inspection up to 15 miles of pipe or up to an area of approximately 72,000 square feet.

It seems possible that the apparent relation between pit depth and area arises, in part at least, from the use of the maximum pit depth as the criterion for corrosivity. The probability that a deeper pit will develop on a large area than on a small area must be a function of the relative sizes of the areas and must always be greater than 50 percent. It seems likely, therefore, that the pit-depth-area relation may be, in part at least, a probability relation, but that it is modified to some extent by certain factors related to soil characteristics. However the relationship may be regarded, it must be taken into account if soil-corrosion data are to be correctly interpreted.

(e) DURATION OF EXPOSURE

The depth of the deepest pit usually is not proportional to the period of exposure of the metal to the soil. This is illustrated by figure 9. A number of empirical equations have been offered to express the relation of pit depth to the duration of the exposure. Fetherstonhaugh [51] suggested the equation $D = A^3\sqrt{T}$, in which D is the depth of the pit at any time, T, and A is the pit depth for unit time of exposure. Put-

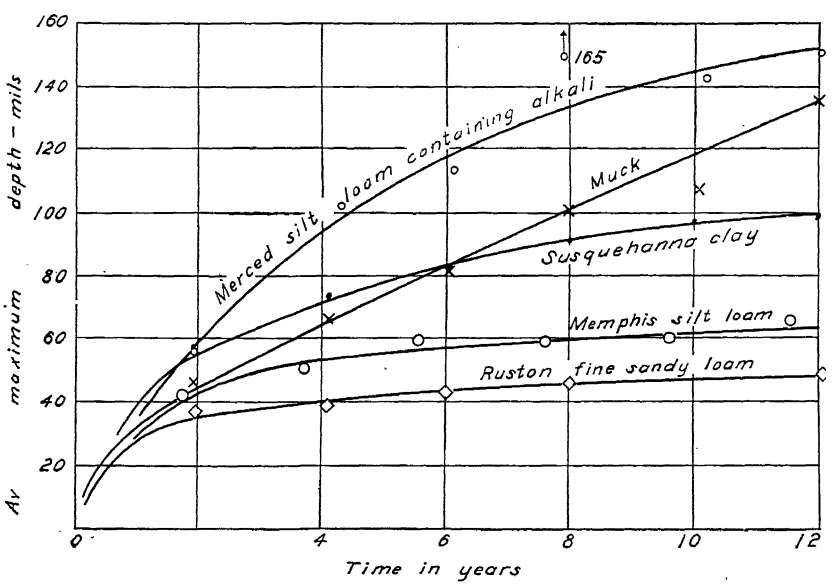

FIGURE 9.—*Relation of maximum depth of pits to duration of exposure.*

nam [52] proposed the equation $P = KT^{0.61}$, which differs from Fetherstonhaugh's equation only in the value of the exponent of T. These equations indicate that the change in pit depths with time follows a similar course in all soils.

Brennan [53], from a study of pipe-line data, decided that the relation of pit depth to time could be represented by the equation $y = (A + BZ) \log (x/h + 1)$, where y is the depth of the pit at a time x, Z is the Corfield soil-corrosivity index [54], and A, B, and h are constants to be derived from a study of test data.

Scott [55], after analyzing the National Bureau of Standards data, concluded that the relation of pit depth to time could be represented approximately by the equation $P = UT/(B + T)$, in which P is the pit depth at time T, and U and B are constants which characterize the soil.

Ewing [35] found that the occurrence of leaks on pipe lines was consistent with the equation $P=kT^n$, in which P is the depth of the deepest pit (on equivalent areas) at time T, and k and n are constants depending on the characteristics of the soil. Denison [56] found that this equation is also applicable to the Bureau's data. This can be shown by plotting the logarithm of the average maximum pit depth on equivalent areas against the logarithm of the time of exposure. Within the error of the observations, the relationship is linear. This equation has the advantage over those of Fetherstonhaugh and Putnam that it need not be assumed that all pit depth-time curves have the same general shape.

In view of the general applicability of the Ewing equation, values of the constants k and n have been determined for the soils at all the National Bureau of Standards test sites for which sufficient data have been accumulated to give reliable values. The value of k appears to be a function of the fundamental corrosivity of the soil, and the value of n seems to be related to the degree of aeration. The degree of aeration of a soil largely determines the effectiveness of the corrosion products in protecting the metal against continued corrosion. Based on this relationship, values of n to be used in the absence of data from which they can be determined directly have been assigned [56] to classes of soil according to their aeration, as follows: Good, 0.188; fair, 0.345; poor, 0.473; very poor, 0.682. The use of three significant figures is usually not warranted by the precision with which the values can be determined for a given soil or class of soils. As a rule, probably not more than one significant figure should be used.

V. RESULTS OF FIELD TESTS ON FERROUS MATERIALS

1. CAST IRON

(a) AFTER 17 YEARS OF EXPOSURE

Table 29 shows the loss of weight, maximum penetration, and the weighted average maximum pit depth of specimens of 6-inch cast-iron pipe exposed for approximately 17 years to 19 of the less corrosive soils of the original National Bureau of Standards test sites. Care should be used in comparing the materials, as about a third of the deLavaud specimens were buried 2 years later than the pit-cast specimens. As has been stated, the depth of the deepest pit is a function of the area from which it is chosen. It has been observed that for small areas consistent results are obtained by averaging a number of pits proportional to the area exposed. Part of the data have been weighted in this table by averaging

TABLE 29.—*Loss of weight and maximum and weighted maximum penetration of 17-year-old cast-iron specimens.*[a]

Soil No.	Soil type	Duration of exposure	Loss of weight			Maximum penetration			Weighted maximum penetration [b]		
			Northern pit cast, L [c](1)	Southern pit cast, Z (1)	deLavaud, C (2)	Northern pit cast, L (1)	Southern pit cast, Z (1)	deLavaud, C (2)	Northern pit cast, L (1)	Southern pit cast, (1)	deLavaud, C (2)
		Years	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*
2	Bell clay	[d]17.58	6.01	4.19	4.72	152	82	104	110	72	78
5	Dublin clay adobe	[d]17.49	10.12	11.62	12.79	119	154	90	114	132	68
6	Everett gravelly sandy loam	[d]17.46	0.90	0.67	0.64	22	30	56	19	27	53
7	Maddox silt loam	16.94	5.16	6.95	5.94	106	86	115	88	78	88
9	Genesee silt loam	16.92	5.31	5.92	5.64	112	110	87	95	103	72
12	Hanford fine sandy loam	[d]17.53	4.12	3.41	[e]1.23	94	70	92	85	62	[e]64
15	Houston black clay	[d]17.58	8.99	6.45	[f]2.00	226	148	54	168	130	[f]50
17	Keyport loam	16.97	9.93	8.92	9.12	175	67	86	96	62	76
24	Merrimac gravelly sandy loam	17.19	0.47	0.81	0.73	27	73	68	22	38	61
25	Miami clay loam	16.99	2.46	2.51	2.12	132	112	92	98	97	71
26	Miami silt loam	16.93	3.20	3.87	2.90	94	157	68	76	138	62
27	Miller clay	[d]17.63	7.41	8.56	6.17	200	204	128	188	168	104
30	Muscatine silt loam	17.04	11.15	8.88	8.17	140	344	170	132	201	150
31	Norfolk fine sand	[d]17.74	2.14	3.19	2.14	62	58	103	50	54	98
35	Romona loam	17.53	4.67	0.72	.....	122	40	.....	100	36	.....
36	Ruston sandy loam	[d]17.68	1.48	1.85	1.63	78	102	75	76	88	68
38	Sassafras gravelly sandy loam	17.22	1.56	1.81	1.70	50	73	65	36	47	53
41	Summit silt loam	17.41	6.15	6.05	3.54	55	94	58	52	84	55
47	Unidentified silt loam	17.43	3.61	6.49	5.99	32	62	83	24	58	80

[a] See table 3 for identification of the specimens.
[b] Average of 4 pits on 1 L or Z specimen, or 4 pits on each of 2 C specimens.
[c] The number in parentheses indicates the number of specimens removed from each site. When more than 1 specimen was removed the average value is given.
[d] The C specimens are approximately 15.5 years old.
[e] Average of 4 specimens.
[f] Data on 1 specimen only.

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TABLE 30.—*Loss of weight, maximum, weighted maximum and estimated average maximum penetration of 12-year-old cast-iron pipe.*

[Data on 1 specimen for L and Z, and on two specimens for C]

Soil[a] No.	Duration of exposure	Loss of weight			Maximum penetration			Weighted maximum penetration			Estimated average maximum pit depth								
		deLavaud, C	Northern pit cast, L	Southern pit cast, Z	deLavaud, C	Northern pit cast, L	Southern pit cast, Z	deLavaud, C	Northern pit cast, L	Southern pit cast, Z	deLavaud, C			Northern pit cast, L			Southern pit cast, Z		
											δ[b]	$\bar{\bar{x}}$[e]	σ_m[d]	δ	$\bar{\bar{x}}$	σ_m	δ	$\bar{\bar{x}}$	σ_m
	Years	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*	*Mils*		*Mils*	*Mils*		*Mils*	*Mils*		*Mils*	*Mils*
1	11.65	12.68	13.47	13.05	127	152	301	115	123	224	0	147.1	9.7	+2	158.4	54.4	0	293.7	15.2
2	[e]12.01	6.38	6.75	5.02	48	62	93	42	57	87	±7	51.1	3.0	±1	141.5	27.3	±1	92.2	3.8
3	[e]12.10	3.18	3.93	4.18	61	135	176	45	120	147	+2 ±6	79.9	9.2	+1	295.5	34.8	0	176.5	2.7
4	[e]12.00	19.13	10.76	10.08	126	95	103	108	90	90	±2	127.7	10.4	+1 ±1	60.0	60.6	−1 ±1	109.8	4.9
5	[e]12.10	10.59	8.49	10.47	76	46	110	61	40	90	±6	73.0	3.5	±2	117.2	31.2	±2	111.4	5.9
[f]6	[e]12.09	0.82	0.94	1.16	22	10	10	12	10	10	.....	.....	.....	.....	.....	.....	.....	.....	.....
7	11.52	6.76	5.67	8.01	88	149	77	82	87	72	±4	63.4	6.0	−1 ±2	139.9	17.7	±3	80.7	22.1
8	11.76	16.84	20.28	30.81	179	240	239	156	217	228	±3	195.8	15.0	0	225.9	19.4	0	43.3	10.2
[f]9	11.51	6.82	6.12	6.56	64	74	72	61	57	62	.....	.....	.....	.....	.....	.....	.....	.....	.....
10	11.95	5.55	5.75	5.29	50	75	79	43	68	63	+1 ±3	43.0	2.9	±1	106.9	23.9	±2	117.1	22.1
11	11.92	1.61	2.00	2.27	46	66	68	42	43	61	±2	84.0	24.1	±1	46.6	4.9	0	82.1	6.6
12	12.10	.....	5.66	4.52	.....	59	89	.....	49	65	([f])	([f])	([f])	±1	41.3	4.6	−1 ±1	89.0	2.4
14	11.76	3.96	4.95	6.15	67	66	60	51	50	53	0	70.3	8.3	0	69.2	7.2	0	69.2	8.9
15	[e]12.02	8.27	8.39	6.87	47	131	114	39	110	91	±6	54.0	3.4	±1	137.9	14.2	+2 ±1	117.1	1.7
16	12.00	.....	10.12	9.13	.....	154	189	.....	148	170	([f])	([f])	([f])	0	223.7	27.9	0	185.4	43.5
17	11.78	10.91	9.22	9.60	84	56	69	74	54	61	±4	95.1	7.6	±2	78.4	20.1	±2	71.4	10.9
18	11.71	2.74	2.66	4.84	85	103	147	69	92	135	−1 ±3	91.8	8.1	−1	124.9	6.6	−1 ±1	147.2	0.5
19	11.63	3.13	5.47	4.56	69	207	259	61	187	171	0	69.4	3.9	−1	205.8	5.1	0	295.3	32.3
20	11.65	6.22	7.68	10.19	97	102	121	90	81	110	−2 ±2	119.4	37.7	±1	107.9	25.4	±2	120.7	1.6
[g]21	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	±6	52.3	3.2	±3	100.9	0.0	±3	57.0	0.0
22	11.65	9.18	8.38	.....	106	176	.....	98	156	.....	0	111.2	5.4	0	162.3	16.3	0	178.2	8.6
23	12.09	28.08	39.54	[h]D	242	322	440+	220	303	440+	0	246.9	13.8	0	339.9	20.9	0	448.7	34.0
[f]24	11.95	0.99	0.70	0.95	41	34	29	33	27	26	.....	.....	.....	.....	.....	.....	.....	.....	.....

25	11.67	3.66	3.47	3.32	50	107	111	45	85	90	±3	45.7	3.9	±1	85.2	15.5	±1	143.9	38.2
[f]26	11.52	3.52	4.49	4.94	76	143	173	72	115	157	.....	.....	.....	.....	.....	.....	.....	.....	.....
27	[e]12.02	10.82	6.65	8.17	103	179	185	91	111	111	±6	102.7	8.2	±2	186.4	23.4	+1	202.7	12.7
28	9.60	5.85	36.65	38.43	65	353	196	57	342	169	±9	65.1	9.0	±2	383.9	67.0	([f])	([f])	([f])
29	[e]12.04	53.26	34.40	20.83	108	203	186	80	181	162	([f])	([f])	([f])	±2	187.0	31.1	0	168.2	24.8
30	11.62	9.28	12.52	9.84	136	143	117	121	123	100	([f])	([f])	([f])	([f])	([f])	([f])	±2	116.7	9.3
[f]31	[e]12.04	4.40	2.34	3.76	52	21	76	38	18	63	.....	.....	.....	.....	.....	.....	.....	.....	.....
32	11.66	4.24	4.09	6.45	74	105	144	68	93	120	±1	84.1	8.3	0	136.1	24.7	0	244.0	85.0
33	11.67	15.85	16.18	19.84	120	201	193	105	160	180	±2	145.6	15.2	±1	219.1	29.3	±1	216.3	38.2
[f]34	12.00	7.59	6.97	7.51	100	78	60	90	67	49	.....	.....	.....	.....	.....	.....	.....	.....	.....
[f]35	[e]12.09	2.68	2.00	6.53	99	33	53	89	29	49	.....	.....	.....	.....	.....	.....	.....	.....	.....
36	[e]12.04	3.62	1.90	2.89	69	61	51	43	49	40	±6	72.0	5.5	{+1, ±1}	246.8	57.2	{+1, ±1}	376.1	71.4
37	[e]12.04	12.04	9.38	20.93	98	73	119	80	57	104	([f])	([f])	([f])	([f])	([f])	([f])	{+1, −1}	115.7	4.6
[f]38	12.01	2.16	2.20	2.20	32	10	10	20	10	10	.....	.....	.....	.....	.....	.....	.....	.....	.....
39	12.00	8.80	9.28	14.29	106	60	125	95	57	100	0	107.5	11.0	+1	52.6	2.4	±1	112.9	5.5
40	[e]12.04	18.56	11.40	13.55	68	74	103	66	71	94	±6	67.0	3.9	0	89.9	9.7	0	110.2	7.8
41	11.99	4.54	5.43	5.37	49	63	66	41	57	60	{−2, ±2}	49.0	1.1	±1	68.7	10.7	±1	65.5	2.9
42	[e]12.03	5.92	17.79	30.39	76	230	311	63	193	274	{+1, −1, ±4}	137.3	13.2	0	208.6	21.2	0	269.1	28.8
43	12.02	20.29	14.94	15.32	178	241	151	142	164	104	0	223.8	41.0	([f])	([f])	([f])	{+1, −1}	142.5	4.0
44	11.61	3.76	3.27	3.97	72	65	69	60	60	61	{+1, −1, ±2}	46.8	10.2	{+1, ±1}	65.7	3.7	±1	62.4	5.6
45	11.73	12.58	6.24	23.75	128	139	142	112	123	140	+4	87.8	6.0	+2	132.9	5.9	+1	186.0	5.8
[f]46	12.00	4.16	5.55	8.08	68	67	102	55	61	98	.....	.....	.....	.....	.....	.....	.....	.....	.....
47	12.08	4.16	3.47	4.27	72	17	33	62	14	28	([f])	([f])	([f])	±1	20.9	2.1	±2	33.0	0.4

[a] See table 19 for identification of soils.
[b] δ denotes the number of specimens omitted in averaging because of unsatisfactory data. The plus or a minus sign before a value in the δ column denotes whether the pitting of the omitted specimens was more or less than the average. A number preceded by a ± sign indicates the number of specimens for which there were no data.
[c] $\bar{\bar{x}}$ denotes the average maximum pit depth.
[d] σ_m denotes the standard error of $\bar{\bar{x}}$.
[e] The C specimens in this soil are approximately 10 years old.
[f] Data unsatisfactory for determining the pit-depth—time curves.
[g] Specimens lost; average pit depths at the close of 6 years.
[h] D =Specimens destroyed; no weight-loss data.

four pits from each 6-inch specimen. The justification for this weighting will be shown later.

If it is assumed that the data are properly weighted, the data in the last three columns of table 29 may be compared with similar data for wrought pipe in table 36 to 37. Such comparison should not be made for specimens exposed for different periods even if reduced to time-rate bases. Likewise, it is not proper to compare unweighted pit depths for specimens of different sizes; for example, the average maximum-pit-depth data in table 30 with similar data for wrought pipe of the same age.

(b) AFTER 12 YEARS OF EXPOSURE

Table 30 is mostly a rearrangement of parts of tables 4, 5, and 7 of Research Paper RP883, Soil-Corrosion Studies, 1934 [45], which reports the data on the examinations of all the 6-inch cast ferrous specimens buried in 1922.

The average maximum pit-depth data were derived in the following way. A procedure was adopted that involves a minimum of assumptions as to similarity of materials, areas, and rates of corrosion. The first step was to plot all of the pit depths for each material in each soil, and to draw arbitrarily smooth curves for the data representing the trend of the data with respect to the duration of the exposure. If no specimens were missing, 6 or 12 points, 1 for each of the L and Z specimens and 2 for the C specimens for each period of exposure were plotted. Points on this curve corresponding to the six periods of exposure were taken off, and the ratios of the last point to each of the others were computed. Then each plotted point or pit depth was multiplied by the ratio for the corresponding time of exposure, thus reducing all pit depths to corresponding pit depth for 12 years of exposure. The average pit depth, the standard deviation, and standard error were then computed for these adjusted observations, that is, for each material in each soil.

The magnitudes of the average pit depth and of the standard error depend, of course, on the way in which the curve referred to was drawn, and it is probable that, in some cases at least, more representative curves could have been drawn. This would have resulted in smaller standard errors and more accurate average values. Nevertheless, the worst result of an improperly drawn curve is an inaccurate average and a large standard error. The two taken together are true for any curve, although they may not be sufficiently precise to be of value. As the purpose of the study was to determine whether or not the differences between the average rates of penetration could be accounted for by the dispersion of the data as indicated by the standard error, there was nothing to be gained by calculating the average rates of penetration for cases where the dispersion was obviously so great that a very large standard error would be obtained. In certain cases an average with a satisfactory standard error could be made by neglecting one or two points on the assumption that such points were the results of abnormal conditions with respect to soil or material. This, however, is a somewhat questionable procedure. Table 30 gives the average maximum pit depths for each cast-iron material in each soil for which a satisfactory standard error could be obtained by the method just outlined.

If all specimens were removed and data from them used, the number of observations or, in statistical terms, the size of the sample was 12. In some mildly corrosive soils two specimens were left in the ground so that they could be examined after a long period of exposure. A few

specimens were lost or destroyed, and a few pit measurements have been neglected for reasons stated above. The table includes a column showing the number of specimens that were omitted from the computations and the reason for the omission. A ± sign followed by a number indicates the number of specimens for which no data were available; a + sign and a number indicate that one or more pit measurements were neglected because the values were so much greater than the estimated values for the period that an extremely large standard error would result if the data were included, and a — sign indicates that the pit depth was much less than the estimated value. It is possible, therefore, for anyone to revise the table by eliminating the soils from which data were deleted without completely recalculating the table.

It will be noted that the average maximum penetrations have not been computed for the cast specimens because there were so many soils in which the data were erratic that averages which would be satisfactory for comparisons could not be obtained. This unsatisfactory condition is due, in part, to the small number of specimens of the cast materials and, in part, to the great dispersion of the data. In some cases the dispersion is the result of extra-deep pits, whereas in others, the cause of the dispersion is the absence of pits of the expected depth. The fact that the cast-iron specimens were larger than the others may to some extent account for the greater dispersion of their data and for the greater maximum pit depths that sometimes appear. Table 33 may be used for comparing the materials listed in the table, but the unweighted data are not comparable without adjustment with similar data for specimens having different exposed areas. The pit-depth–area for relation will be discussed later. The standard error is an indication of the reproducibility of the data. Roughly speaking, if the tests were repeated, the odds against a second average differing from the first by more than twice the standard error are about 20 to 1.

The probability that two average values are really different may be determined from the equation

$$\sigma_D = \sqrt{\frac{\sigma_1^2}{N_1} + \frac{\sigma_2^2}{N_2}},$$

in which

σ_1 = standard error of average No. 1.
σ_2 = standard error of average No. 2.
N_1 = number of observations in average No. 1.
N_2 = number of observations in average No. 2.
σ_D = standard error of difference.

If the difference between the two averages is more than $2\sigma_D$, the chances are about 20 to 1 that the difference is not due to chance. If the difference is more than $3\sigma_D$, the chances that the difference is real are about 997 in 1,000. To illustrate, for soil 1 the average of the deepest pits on 12 C specimens was 147.1 mils, with a standard error of 9.7 mils, whereas the average of the deepest pits on 6 specimens of southern cast iron, Z, was 293.7 mils, with a standard error of 15.2 mils. The standard error of the difference, 293.7—147.1, or 146.6 mils, is

$$\sqrt{\frac{(9.7)^2}{12} + \frac{(15.2)^2}{6}} = \sigma = 6.80,\ 3\sigma = 20.4.$$

It is, therefore, highly probable that the difference of 146.6 mils is significant. On the other hand the standard error of the difference between

the pit depths on the C and L specimens in soil 1 is 38.56, whereas the difference between the pit depths is only 11.3. The difference is, therefore, probably accidental. This is due to the large standard error of the L specimens. Statistical treatment of the Bureau's soil-corrosion data is not entirely satisfactory because of the dispersion of the data and the limited number of the specimens subjected to one set of conditions, and because the necessary assumptions as to the distribution of the data are not strictly correct. However, such treatment serves a very useful purpose in that it calls attention to the limitations of the data. Some idea of the magnitude of an investigation that would give entirely satisfactory data can be obtained from the fact that the Bureau has exposed over 36,000 specimens and from the magnitude of the standard errors of the data. Consideration of these facts will make it evident that to obtain satisfactory data, it would be necessary to increase the number of specimens subject to a single set of conditions, and to limit the varieties of specimens and conditions. Whether or not the same investment with these limitations would yield more useful information is debatable.

(c) AFTER 9 YEARS OF EXPOSURE

The results of examinations of specimens buried in 1922, some of which appear in table 30, indicated that some soils were severely corrosive and that pipe materials more resistant to corrosion were desirable. In 1932 the Bureau invited manufacturers to submit specimens of materials believed to be suitable for service in 15 soils selected because of their corrosivity with respect to the commonly used ferrous pipe materials. The materials submitted are the bases for the so-called tests of corrosion-resistant materials. The tests will not be completed until after the war, but data so far obtained indicate in a general way what may be expected [57].

Table 31 shows the losses of weight and maximum penetration of six varieties of cast iron. The specimens were about 14 inches long and 1½ inches in diameter and were laid in a horizontal position across the trenches. The table is comparable only with tables 41 and 42, which show data on steel specimens of the same size and age. As table 31 is based on the performance of only two specimens of a kind, the data cannot be treated statistically.

To provide a more reliable basis for comparing materials and soils, tables 32 and 33 have been prepared. For each of the four periods of exposure, the losses of weight and maximum pit depths for each material in each of 12 soils for which the data were complete were expressed as percentages of the averages of the loss of weight and the maximum pit depths in all of the 12 soils. The results for the four periods were then averaged to form tables 32 and 33. This permits a comparison of the materials in each soil and of the corrosiveness of each soil with respect to each material. By taking the value of N as 8, the number of specimens of one kind in each soil, the standard error of the difference for any two materials or soils can be computed and the significance of the difference determined. Without the computations it is almost obvious that some of the soils are more corrosive than others, and that the high alloy, E, is the only material definitely superior to the others.

TABLE 31.—*Loss of weight and depth of maximum penetration of cast-iron pipe exposed for 9 years.*

[Average for 2 specimens. Each ounce per square foot corresponds to an average penetration of 0.0017 inch.]

Soil No.	Soil type	Duration of exposure	Horizontally cast in sand mold			Low alloy —						High alloy —	
			Sand-coated, F. Maximum penetration	Rattled, G.[h] Loss of weight	Rattled, G.[h] Maximum penetration	I. Loss of weight	I. Maximum penetration	J. Loss of weight	J. Maximum penetration	C. Loss of weight	C. Maximum penetration	E. Loss of weight	E. Maximum penetration
		Years	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
53	Cecil clay loam	9.47	[a][b]75	3.25	[b]57	2.76	58	2.55	62	2.25	[a][b]66	1.35	[b]33
55	Hagerstown loam	9.11	[b]98	3.55	[c]123	2.67	108	[b]2.10	[a][c]96	2.04	123	[c]0.72	[b]34
56	Lake Charles clay	9.42	[d]250+(7)	[e]D(42)	250+(7)	37.34	249	33.71	215	29.70	216+	14.62	58
58	Muck	9.51	250+(7)	20.08	250+(5, 7)	24.05	240	27.10	233	21.88	250+	9.91	[b][c]53
59	Carlisle muck	9.12	[c]44	[a][b]3.60	52	4.08	74	[b]2.92	[c]49	[a]2.37	24	0.66	26
60	Rifle peat	9.24	[a]163+	20.77	[a]175+	[a]18.15	[a]140	[a]17.01	[a]130	[a]13.07	[a]93	[a]10.00	[a]45
61	Sharkey clay	9.53	78	7.08	78	7.54	113	6.89	80	7.21	119	2.33	[a]36
62	Susquehanna clay	9.47	[b]90	8.10	[a][b]81	6.61	[b]91	6.37	[a][b]63	6.92	[c]80	2.73	53
63	Tidal marsh	9.55	131	6.14	114	[a]9.98	104	[a]11.40	85	2.56	[b]40	1.63	[a][b]32
64	Docas clay	9.21	250+	D(34)	250+	46.83	317+	44.59	246	[b][f]41.93	[f]250+	12.82	74
65	Chino silt loam	9.25	145	7.62	131	11.04	172	10.28	156	14.61	161	[a]2.55	[b]35
66	Mohave fine gravelly loam	9.23	[b]118	[b]3.96	[b]152(7)	8.22	214	12.15	[b]193	10.74	[b]141	[a][c]3.29	40
67	Cinders	9.24	250+(5, 7)	D	250+(5, 7)	[g]61.41+	327+(5)	[g]64.99+	[b]266+(5, 7)	45.74	[b]195+(5, 7)	52.33	250+(5, 7)

[a] Data for individual specimens differed from each other by more than 50% of the larger value.
[b] Average maximum pit depths or loss of weight of the 1939 removals are greater. The single maximum value of the 1939 removals are greater.
[c] Average maximum pit depths or loss of weight of the 1939 removals are greater. The single maximum value of the 1941 removals are greater.
[d] The plus (+) sign indicates that 1 or both specimens were punctured. A number in parentheses after the pit depth indicates that 1 or both specimens of a previous removal was punctured, i.e., (2) indicates a puncture after 2 years of exposure, etc.
[e] D indicates that both specimens were destroyed. The number in parentheses is the approximate loss of weight.
[f] Data for 1 specimen only.
[g] Data for 1 specimen only. The other specimen was destroyed by corrosion.
[h] same as F, except with sand removed.

TABLE 32.—*Average of the relative loss of weight of the cast materials for four periods of exposure.*

[In percent]

Soil No.	Rattled, G[a]		Low alloy, I		Low alloy, J		Low alloy, C		High alloy, E		Average
	Relative loss	Standard error	Relative loss	Standard error	Relative loss	Standard error	Relative loss	Standard error	Relative loss	Standard error	
53	42	14	30	8	30	9	34	11	13	2	30
55	36	5	30	6	34	14	30	10	9	2	28
56	246	36	205	53	203	42	187	28	89	14	186
58	166	24	175	33	172	37	190	11	67	18	154
59[b]	37	4	34	0	33	3	24	3	22	16	25
60	129	31	128	21	112	18	104	22	61	16	107
61	50	12	56	14	57	15	52	11	18	4	47
62	82	13	70	16	74	15	67	17	20	3	63
63	45	11	53	10	66	12	32	7	10	1	41
64	308	39	376	38	387	47	394	58	74	12	256
65	104	27	128	29	130	24	164	26	29	6	111
66	74	16	73	7	99	6	118	22	42	5	81
Average	110	.....	113	.....	116	.....	116	.....	38	.....	.....

[a] See table 9 for composition of the materials.

TABLE 33.—*Average of the relative maximum penetration of the cast materials for four periods of exposure.*

[In percent]

Soil No.	Sand-coated, F[a]		Rattled, G		Low alloy, I		Low alloy, J		Low alloy, C		High alloy, E		Average
	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	
53	84	9	69	9	57	15	72	14	70	9	48	7	67
55	100	11	100	10	79	11	85	5	83	10	46	7	82
56	177	35	171	38	145	35	138	29	134	23	58	10	137
58	156	30	191	48	156	26	146	29	162	24	63	14	146
[b]59	52	12	47	11	55	6	49	3	18	3	23	2	41
60	89	20	93	24	86	9	72	17	67	18	56	6	77
61	60	5	77	4	91	12	70	9	61	18	48	10	68
62	105	15	115	13	119	30	98	19	106	21	60	12	100
63	74	13	77	14	75	12	92	11	51	27	38	7	68
64	198	26	190	29	208	35	188	23	212	32	49	5	174
65	101	8	114	8	126	3	127	6	127	5	46	7	107
66	109	6	136	14	132	23	142	23	147	14	44	5	118
Average	109	.....	115	.....	111	.....	107	.....	103	.....	48	.....	.....

[a] See table 9 for the composition of the materials.
[b] Data for only 3 periods of exposure.

(d) AFTER 2 YEARS OF EXPOSURE

The cast-iron specimens exposed for 2 years consist of 12- by 3½- by ½-inch sections of 12-inch class 150 Super deLavaud pipe bolted to flat 12- by 3½- by ⅜-inch charcoal cast-iron plates by means of steel and charcoal cast-iron bolts.

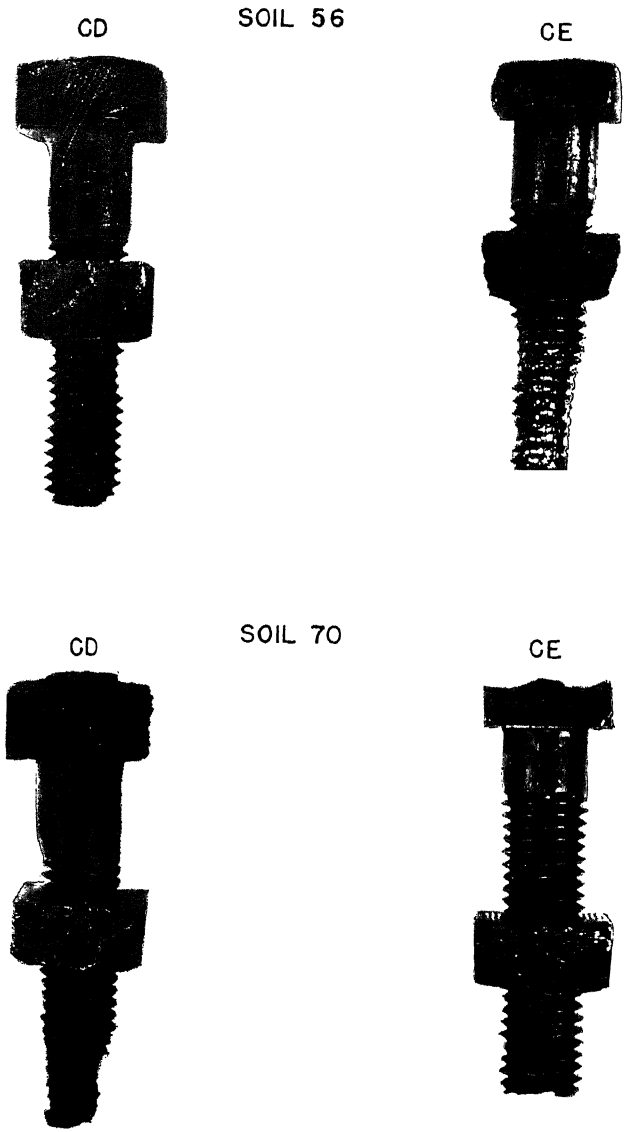

FIGURE 10.—*Charcoal cast iron CD, and steel CE, bolts exposed to both soils 56 and 70 for approximately 2 years each.*

Table 34 indicates that the charcoal cast iron lost more weight than the Super deLavaud iron in most soils, and in all but one soil the maximum pit depths on the Super deLavaud cast iron were definitely less

than on the charcoal cast iron. This might be attributed to galvanic action between the different metals in addition to the other causes of corrosion. Figure 10 shows the condition of the cast-iron and steel bolts connected to the couples in soils 56 and 70.

TABLE 34.—*Loss of weight and depth of maximum penetration of cast-iron plates and cast-iron and steel bolts (the plates were connected by the bolts).*

[Exposure 2 years]

Soil		Exposure	deLavaud cast iron CC		Charcoal cast iron CB		Nuts and bolts	
							Steel CE	Charcoal cast iron, CD
No.	Type		Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Loss of weight
		Years	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*oz/ft²*
53	Cecil clay loam	1.91	1.21	30	1.59	38	1.92	1.81
55	Hagerstown loam	2.03	1.03	32	1.05	68	1.28	1.56
56	Lake Charles clay	1.91	6.13	45	11.27	74	20.10	9.04
58	Muck	1.91	5.98	42	4.10	58	6.47	7.12
60	Rifle peat	1.91	4.27	23	3.21	41	5.06	3.32
61	Sharkey clay	1.92	1.66	36	2.56	58	2.54	2.28
62	Susquehanna clay	1.90	2.52	34	2.73	57	2.57	3.31
63	Tidal marsh	1.88	1.94	36	2.69	57	(a)	(a)
64	Docas clay	1.90	4.53	36	4.64	57	3.28	b5.54
65	Chino silt loam	1.91	1.89	34	3.39	54	4.24	3.85
66	Mohave fine gravelly loam	1.86	4.88	34	6.28	54	(a)	(a)
67	Cinders	1.90	18.48	88	20.67	102	16.22	18.18
69	Houghton muck	1.90	2.25	38	2.08	36	1.71	1.86
70	Merced silt loam	1.90	7.40	96	10.50	122	b11.19	10.12

[a] Both specimens missing.
[b] Loss of weight for individual specimens different from each other by more than 50 percent.

(e) HIGH-SILICON CAST IRON

Included in the materials buried in 1922 were specimens of Duriron, a cast iron containing about 14 percent of silicon. The material is not machinable, but is used extensively for chemical plumbing. With a very few exceptions, the losses after from 10 to 12 years' exposure were negligible. There was no pitting or softening except along cracks in the specimens in soil 28, Montezuma clay adobe. Similar corrosion was found in this soil on two previous inspections, and on one inspection softening in spots occurred in Muck. Detailed data on high-silicon cast iron may be found in Research Paper RP883 [45].

(f) MALLEABLE CAST IRON

The corrosion of gray cast iron starts at and tends to follow the boundaries between the graphite plates and the ferrite crystals. The heat treatment which malleable iron receives slightly reduces the total carbon content and the free carbon takes the form of small rounded particles. The Bureau tests did not include a sufficient number of specimens to justify a generalization as to the relative corrodibility of gray and malleable cast iron.

Table 35 shows the data for the longest period of exposure. To the data on malleable iron have been added data on specimens of high-tensile-strength cast iron and cast steel. Data on ordinary cast iron have been added for comparison. The malleable iron and cast steel specimens were in the form of elbows and with available apparatus it

(d) AFTER 2 YEARS OF EXPOSURE

The cast-iron specimens exposed for 2 years consist of 12- by 3½- by ½-inch sections of 12-inch class 150 Super deLavaud pipe bolted to flat 12- by 3½- by ⅜-inch charcoal cast-iron plates by means of steel and charcoal cast-iron bolts.

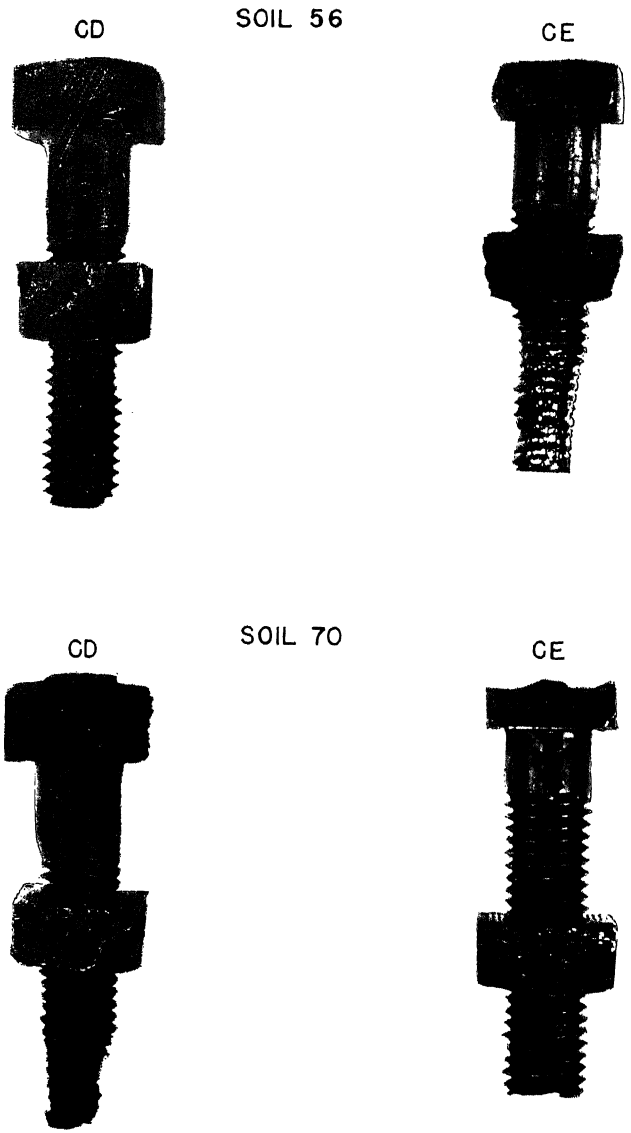

FIGURE 10.—*Charcoal cast iron CD, and steel CE, bolts exposed to both soils 56 and 70 for approximately 2 years each.*

Table 34 indicates that the charcoal cast iron lost more weight than the Super deLavaud iron in most soils, and in all but one soil the maximum pit depths on the Super deLavaud cast iron were definitely less

than on the charcoal cast iron. This might be attributed to galvanic action between the different metals in addition to the other causes of corrosion. Figure 10 shows the condition of the cast-iron and steel bolts connected to the couples in soils 56 and 70.

TABLE 34.—*Loss of weight and depth of maximum penetration of cast-iron plates and cast-iron and steel bolts (the plates were connected by the bolts).*

[Exposure 2 years]

Soil		Exposure	deLavaud cast iron CC		Charcoal cast iron CB		Nuts and bolts	
							Steel CE	Charcoal cast iron, CD
No.	Type		Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Loss of weight
		Years	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*oz/ft²*
53	Cecil clay loam	1.91	1.21	30	1.59	38	1.92	1.81
55	Hagerstown loam	2.03	1.03	32	1.05	68	1.28	1.56
56	Lake Charles clay	1.91	6.13	45	11.27	74	20.10	9.04
58	Muck	1.91	5.98	42	4.10	58	6.47	7.12
60	Rifle peat	1.91	4.27	23	3.21	41	5.06	3.32
61	Sharkey clay	1.92	1.66	36	2.56	58	2.54	2.28
62	Susquehanna clay	1.90	2.52	34	2.73	57	2.57	3.31
63	Tidal marsh	1.88	1.94	36	2.69	57	(a)	(a)
64	Docas clay	1.90	4.53	36	4.64	57	3.28	b5.54
65	Chino silt loam	1.91	1.89	34	3.39	54	4.24	3.85
66	Mohave fine gravelly loam	1.86	4.88	34	6.28	54	(a)	(a)
67	Cinders	1.90	18.48	88	20.67	102	16.22	18.18
69	Houghton muck	1.90	2.25	38	2.08	36	1.71	1.86
70	Merced silt loam	1.90	7.40	96	10.50	122	b11.19	10.12

[a] Both specimens missing.
[b] Loss of weight for individual specimens different from each other by more than 50 percent.

(e) HIGH-SILICON CAST IRON

Included in the materials buried in 1922 were specimens of Duriron, a cast iron containing about 14 percent of silicon. The material is not machinable, but is used extensively for chemical plumbing. With a very few exceptions, the losses after from 10 to 12 years' exposure were negligible. There was no pitting or softening except along cracks in the specimens in soil 28, Montezuma clay adobe. Similar corrosion was found in this soil on two previous inspections, and on one inspection softening in spots occurred in Muck. Detailed data on high-silicon cast iron may be found in Research Paper RP883 [45].

(f) MALLEABLE CAST IRON

The corrosion of gray cast iron starts at and tends to follow the boundaries between the graphite plates and the ferrite crystals. The heat treatment which malleable iron receives slightly reduces the total carbon content and the free carbon takes the form of small rounded particles. The Bureau tests did not include a sufficient number of specimens to justify a generalization as to the relative corrodibility of gray and malleable cast iron.

Table 35 shows the data for the longest period of exposure. To the data on malleable iron have been added data on specimens of high-tensile-strength cast iron and cast steel. Data on ordinary cast iron have been added for comparison. The malleable iron and cast steel specimens were in the form of elbows and with available apparatus it

was impracticable to determine pit depths on these specimens. Inspection indicated that the pitting did not differ greatly in form and extent from that on ordinary cast iron under the same conditions. A little additional information on the relative corrodibility of malleable cast iron and steel will be found in the section on the corrosion of bolts, table 50.

The specimens in table 35 differ considerably in the area exposed and in shape. The gray cast-iron specimens were much larger than the others, were buried at different times, and were exposed for somewhat different periods. The other materials seem to corrode somewhat less than the cast iron, but the differences are not large and may be accidental.

TABLE 35.—*Corrosion of malleable cast iron and cast steel.*

Soil No.	Soil type	Duration of exposure	Malleable cast-iron cell, S. Loss of weight	Cast steel cell, E. Loss of weight	High-tensile-strength cast iron, V		Gray cast iron, L	
					Loss of weight	Maximum penetration	Loss of weight	Maximum penetration
		Years	*oz/ft²*	*oz/ft²*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
13	Hanford very fine sandy loam.	10.16	13.41	19.81	10.87	126	.....	.....
24	Merrimac gravelly sandy loam.	10.63	1.11	4.02	1.06	40	4.74	27
28	Montezuma clay adobe.....	9.60	13.44	16.03	.....	.....	[a]36.65	[a]353
29	Muck.....	10.08	10.58	11.69	11.89	100	15.21	145
42	Susquehanna clay.....	10.05	7.14	7.44	5.73	104	11.27	172
43	Tidal marsh.....	10.73	21.35	8.69	11.70	163	11.42	157
45	Unidentified alkali soil.....	10.55	17.62	19.94	22.05	161	17.65	232

[a] Duration of exposure 11.67 years.

2. WROUGHT FERROUS MATERIAL

This group of materials includes all rolled ferrous materials, such as open-hearth iron, wrought iron, Bessemer steel, and open-hearth steel, together with alloys, irons, and steels that have been rolled into their final forms.

(a) AFTER 17 YEARS OF EXPOSURE

Table 36 and the weighted pit depths of table 37 are comparable with similar data in table 29 and present the data for the oldest wrought specimens. The weighting was based on the area of the specimens, that is, the single deepest pit on each 1½-inch specimen and the two deepest pits on each of two 3-inch specimens. As a check on this weighting, the corresponding pit depths of the 1½-inch and the 3-inch wrought-iron specimens may be compared. The same companies furnished both materials. Although the averages for all soils indicate that the weighting favors the 1½-inch material, there are 8 soils in which the weighted pit depths are greater for the smaller specimens compared with 10 soils in which the pit depths are less. The "e" and "y" specimens may be compared with the M specimens. It is possible that the amount of rolling or heating required to join the two sizes of pipe or the curvatures of the pipes may be a factor affecting the pit depths.

[Average of two specimens in ounces per square foot.]

Soil No.	Soil type	Duration of test	Open-hearth iron, a	1½-inch pipe			3-inch pipe			
				Wrought iron, b, d	Bessemer steel, e	Bessemer steel, y	Wrought iron, B, D	Open-hearth steel, K	Bessemer steel, M	Open-hearth steel with 0.2% Cu, Y
		Years								
2	Bell clay	17.58	7.83	8.40	7.83	8.11	8.11	7.73	7.12	7.44
5	Dublin clay adobe	17.49	7.16	9.50	[a]7.12	8.31	9.37	11.14	8.58	9.16
6	Everett gravelly sandy loam	17.46	2.20	1.66	2.03	1.53	1.89	1.91	1.88	2.03
7	Maddox silt loam	16.94	7.60	5.49	5.82	6.40	5.62	5.74	5.06	5.08
9	Genessee silt loam	16.94	5.40	5.99	5.80	5.35	5.47	5.39	5.10	5.20
12	Hanford fine sandy loam	17.53	7.18	5.62	6.04	5.57	5.41	4.80	5.32	5.88
15	Houston black clay	17.58	12.35	12.39	10.95	10.41	12.51	15.98	11.21	7.57
17	Keyport loam	16.97	7.94	8.78	9.54	8.42	9.50	9.40	9.51	8.92
24	Merrimac gravelly sandy loam	17.19	1.27	1.88	1.79	1.40	1.39	1.31	1.56	1.24
25	Miami clay loam	16.99	3.02	4.20	3.79	3.09	2.80	3.23	2.73	2.71
26	Miami silt loam	16.93	4.03	5.10	4.28	4.12	4.66	4.11	4.77	4.32
27	Miller clay	17.63	9.33	11.42	10.14	9.34	9.73	8.53	8.86	8.43
30	Muscatine silt loam	17.04	6.08	5.90	5.72	5.46	6.05	5.99	6.90	6.36
31	Norfolk fine sand	17.74	4.86	4.16	3.72	4.39	6.34	4.53	4.08	4.56
35	Ramona loam	17.53	1.54	[b]4.13	1.51	0.92	1.22	0.89	[b]3.21	[b]3.33
36	Ruston sandy loam	17.68	3.28	4.11	4.13	3.73	2.54	2.95	2.58	3.10
38	Sassafras gravelly sandy loam	17.22	2.71	3.35	2.30	2.57	2.34	2.82	2.81	2.50
41	Summit silt loam	17.41	5.87	7.42	6.87	6.96	5.51	5.50	7.03	6.99
47	Unidentified silt loam	17.43	5.80	6.36	7.86	8.35	6.10	6.48	5.38	5.11

[a] Data for 1 specimen only.
[b] Loss of weight of the individual specimens differed from the average by more than 50% of the larger loss.

TABLE 37.—*Maximum penetration and weighted maximum penetration of 17-year-old wrought ferrous pipe.*

[Average of 2 specimens; in mils.]

Soil No.	Duration of exposure	Maximum penetration								Weighted maximum penetration[a]			
		1½-inch pipe				3-inch pipe				3-inch pipe			
		Open-hearth iron, a	Wrought iron, b, d	Bessemer steel, e	Bessemer steel, y	Wrought iron, B, D	Open-hearth iron, K	Bessemer steel, M	Open-hearth 0.2% Cu steel, Y	Wrought iron, B, D	Open-hearth iron, K	Bessemer steel, M	Open-hearth 0.2% Cu steel, Y
	Years												
2	17.58	71	60	56	64	47	70	58	67	46	62	56	64
5	17.49	76	45	[b]51	42	65	91	62	71	62	82	58	68
6	17.46	27	31	19	20	32	30	21	26	30	27	19	25
7	16.94	48	36	50	61	74	67	48	57	57	55	47	51
9	16.94	69	51	64	67	68	55	62	109	58	53	57	95
12	17.53	70	48	72	64	76	55	85	69	70	54	83	67
15	17.58	63	58	57	56	61	66	52	62	60	56	47	60
17	16.97	42	38	41	34	43	50	49	57	41	46	44	51
24	17.19	27	24	16	26	31	27	36	28	29	25	30	24
25	16.99	73	50	42	43	54	62	56	57	51	54	52	54
26	16.93	43	43	43	36	42	60	58	53	41	57	54	49
27	17.63	40	58	70	54	74	93	84	68	68	84	78	59
30	17.04	50	44	52	43	53	65	76	65	51	63	72	60
31	17.74	50	42	43	52	41	90	66	49	40	83	64	47
35	17.53	12	54	9	17	33	33	37	64	31	28	31	56
36	17.68	51	50	55	45	50	60	49	57	50	59	48	53
38	17.22	41	33	28	36	34	38	35	33	31	33	33	31
41	17.41	122	94	93	101	87	68	101	78	81	61	94	70
47	17.43	42	53	37	57	50	40	48	47	48	38	47	44

[a] The maximum penetration and the weighted maximum penetration for the 1½-inch pipe have the same value.
[b] Data for 1 specimen only.

(b) AFTER 12 YEARS OF EXPOSURE

Tables 38, 39, and 40 contain the same kind of information as table 33 and show the data for 12-year-old wrought pipe. Only the weighted pit depths on specimens of different size should be compared without adjustment. As a very rough average factor for comparing unweighted pit depths one may assume that for small changes in area, doubling the area increases the maximum pit depth on ferrous pipe about 10 percent. However, the pit-depth–area relation is somewhat different for different soils and materials.

At the bottom of the tables 39 and 40, average rates of corrosion for most of the soils are given. The difference in the soils is so great that average rates for all soils have little value, except that they permit a comparison of different materials exposed to the same conditions. These averages have been shown graphically in figure 11. As the pit depths were not adjusted to take account of the areas of the specimens, only materials of the same size are strictly comparable.

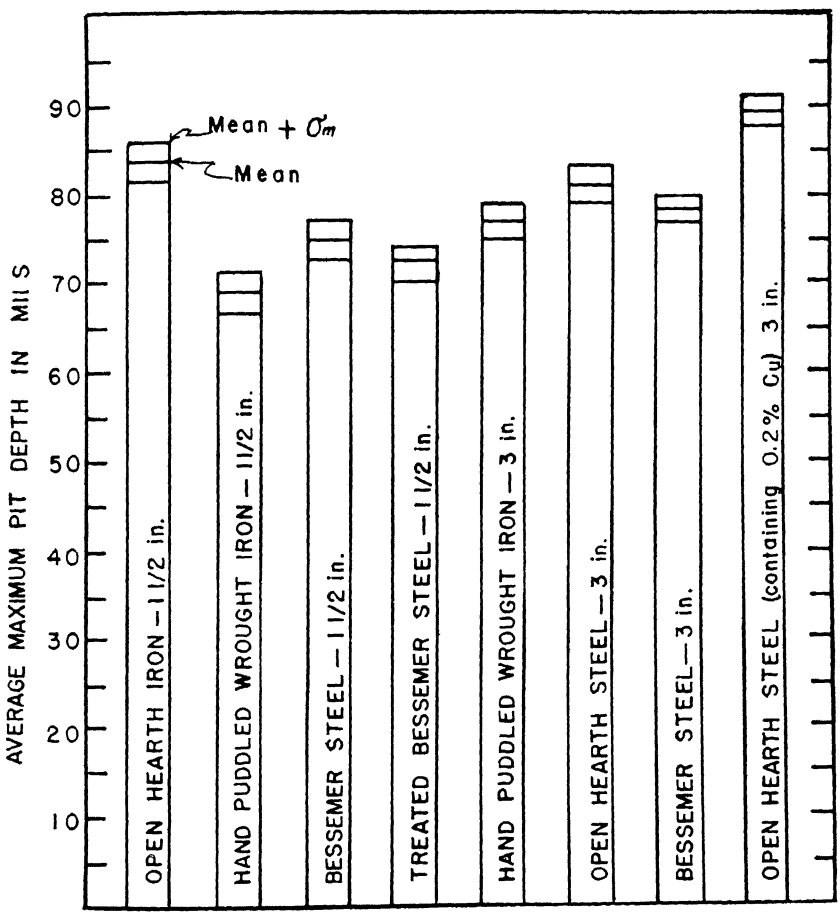

FIGURE 11.—*Average maximum pit depth on wrought pipe for 12 years of exposure; 23 soils.*

The figure 11 indicates that there may be a real difference between open-hearth iron specimens and the other 1½-inch wrought specimens,

as the difference between the average pit depth of the iron and that of the other 1½-inch specimens is approximately twice the sum of the standard errors of the materials. Similarly, the 3-inch open-hearth steel containing 0.2 percent of copper may corrode at a different rate from that of the steel to which copper was not added. In both cases the reason for the differences may be the character of the surfaces of the specimens employed, and the conclusions might not apply to materials having similar compositions but different surface finishes. In the case of the open-hearth iron, the surfaces of the specimens were covered by an almost continuous thin oxide film which broke down in a relatively few places, thus concentrating the galvanic action. A basis for this suggestion is the low loss of weight of the specimens of this material.

The copper-bearing steel specimens, on the other hand, carried unusually heavy patches of mill scale at certain points on their surfaces. It is possible that galvanic action between this mill scale and the remainder of the surface of the pipe accelerated the corrosion, or that after a period of exposure the mill scale became loosened and galvanic action between the unprotected spots and the oxidized areas caused additional corrosion. Care should be exercised in generalizing from the tests of the material from a single source.

The average penetration is smallest for the wrought-iron specimens, but the difference between the average maximum rates of penetration for wrought-iron and Bessemer steel is not sufficient to show positively a difference in the rates of corrosion of these materials for either the 1½-inch or the 3-inch specimens. Although it cannot be said that the materials do not differ, the figure indicates that on the average the rates of penetration do not differ greatly.

Figure 11 indicates also that the maximum pits are generally deeper on the 3-inch than on the 1½-inch specimens, but tables 39 and 40 show that this is not always the case.

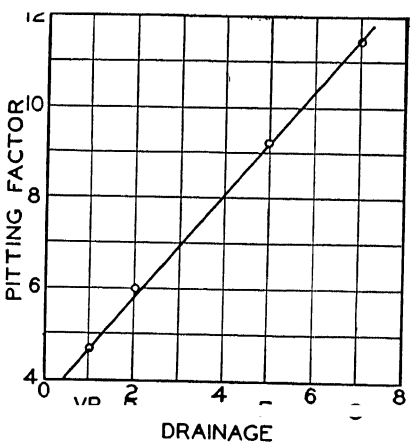

FIGURE 12.—*Correlation between pitting factor and drainage.*

One of the early observations concerning the soil-corrosion specimens was that the corrosion was not uniform and that this lack of uniformity was different for different soil conditions and different materials. The term "pitting factor" is used to designate the ratio of the maximum to the average depth of penetration by corrosion. The pitting factor is an

indication of the uniformity of corrosion and tends to become less as specimens grow older. For the specimens in tables 36 to 40 it ranges between 2 and 40. If the soils are divided into four groups with respect to drainage (aeration), as in table 5, and values 1, 2, 5, and 7 assigned to the terms "very poor," "poor," "fair," and "good," respectively, and if the pitting factors of all the wrought materials in each soil are computed from tables 32 to 40 and plotted against the values of the soil drainage, figure 12 results. The curve indicates that the pitting factor is lowest for the very poorly drained soils. The pitting factor gives no indication of the depth of the corrosion nor the number of deep pits, and it is not an adequate expression of the seriousness or the distribution of corrosion. It tends to be larger for larger specimens.

(c) AFTER 9 YEARS OF EXPOSURE

Tables 41 and 42 show the loss of weight and maximum penetration of 9-year-old wrought specimens. These data are comparable with those in table 31 as approximately the same areas were exposed. Tables 43 and 44 were prepared in order to provide a better basis for comparison of materials by the same method as that used in the preparation of tables 32 and 33. The number of specimens of each material from each site was eight. The standard errors are so large that probably the difference between the materials is not significant. There appears to be a real difference in the corrosivities of the soils. Figure 13 shows graphically the averages given in tables 43 and 44, and indicates that with respect to the relative average values of all materials in the 10 soils for th 4 periods of exposure, nickel-copper steel (D) is better with respect t pitting and loss of weight. However, it should be noted that the mil scale had been removed from these specimens prior to burial. This migh have had an effect on the pitting, as will be evident when the data on the nickel-copper steel given in the following section are compared with the data for a steel of similar composition, but from which the mill scale had been removed.

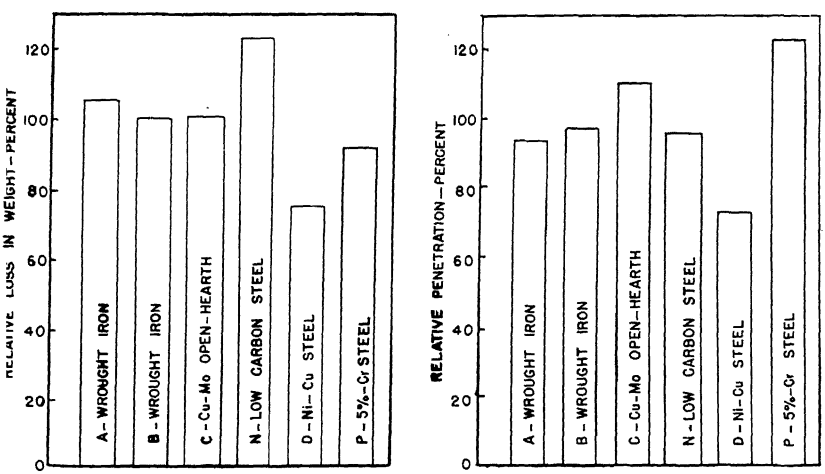

FIGURE 13.—*Relative loss of weight and maximum penetration of wrought ferrous for four periods of exposure.*

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TABLE 38.—*Loss of weight of 12-year-old wrought ferrous pipe.*

[Average of two specimens, in ounces per square foot.]

Soil No.	Soil type	Duration of exposure	1½-inch pipe				3-inch pipe			
			Open-hearth iron, a	Wrought iron, b, d	Bessemer steel, e	Bessemer steel, y	Wrought iron, B, D	Open-hearth iron, K	Bessemer steel, M	Open-hearth steel with 0.2% Cu, Y
		Years								
1	Allis silt loam	11.65	8.92	8.77	7.03	9.29	9.56	9.45	[a]11.56	8.81
2	Bell clay	12.01	[a]5.95	7.12	[a]5.81	5.92	6.32	5.37	[a]6.59	5.91
3	Cecil clay loam	12.10	3.71	4.90	4.69	5.14	4.62	4.17	4.34	4.55
4	Chester loam	12.00	7.03	6.61	6.70	6.23	7.11	6.96	6.92	7.47
5	Dublin clay adobe	12.10	6.46	7.58	7.03	5.46	6.42	7.31	7.32	7.15
6	Everett gravelly sandy loam	12.09	0.99	1.17	1.45	0.91	1.12	1.07	1.52	1.32
7	Maddox silt loam	11.52	4.95	5.14	4.91	[a]4.30	4.82	4.91	5.64	5.65
8	Fargo clay loam	11.76	8.40	6.91	7.69	6.48	8.66	7.94	8.29	8.80
9	Genesee silt loam	11.51	4.73	4.76	5.21	4.96	4.89	5.03	4.58	4.70
10	Gloucester sandy loam	11.95	4.29	5.45	4.88	4.35	4.81	4.38	4.94	5.12
11	Hagerstown loam	11.92	1.69	[a]2.75	2.08	1.87	1.97	1.98	1.74	2.18
12	Hanford fine sandy loam	12.10	3.35	[a]4.42	4.07	[a]3.92	4.01	3.59	3.60	[a]3.30
14	Hempstead silt loam	11.76	4.09	4.53	5.21	4.54	[a]4.78	4.28	4.58	4.68
15	Houston black clay	12.02	8.07	8.55	7.69	7.83	8.30	8.15	8.11	9.09
16	Kalmia fine sandy loam	12.00	8.28	8.25	8.01	7.33	7.68	7.58	7.51	7.56
17	Keyport loam	11.78	9.45	8.61	8.34	9.02	10.56	10.22	9.65	9.96
18	Knox silt loam	11.71	2.95	2.67	3.06	2.64	2.03	2.73	2.40	3.86
19	Lindley silt loam	11.63	2.90	3.50	3.82	3.42	3.25	3.45	3.32	3.48
20	Mahoning silt loam	11.65	6.63	6.54	6.10	6.01	5.63	6.12	5.99	5.65
22	Memphis silt loam	11.65	6.97	7.64	7.52	7.06	7.93	6.89	7.78	7.00
23	Merced silt loam	12.09	20.14	21.13	19.80	20.42	20.71	19.58	19.80	[a]24.34
24	Merrimac gravelly sandy loam	11.95	1.26	1.36	1.55	1.39	1.23	1.43	1.40	1.24
25	Miami clay loam	11.67	3.40	[a]3.97	3.45	2.90	2.81	3.64	3.31	2.78
26	Miami silt loam	11.52	3.53	4.25	3.62	3.47	3.97	3.68	3.77	3.44
27	Miller clay	12.02	7.08	8.55	8.79	7.57	8.32	6.96	8.23	8.08
28	Montezuma clay adobe	9.60	15.67	15.43	16.38	16.78	16.81	16.19	15.54	17.69
29	Muck	12.04	21.49	16.19	19.26	19.44	15.59	17.92	14.84	20.11
30	Muscatine silt loam	11.62	5.18	5.57	4.82	5.30	6.30	5.76	5.63	5.18
31	Norfolk fine sand	12.04	2.87	2.99	2.85	2.69	2.75	2.79	2.76	3.43
32	Ontario loam	11.66	3.10	3.52	3.26	3.69	3.62	3.62	4.15	3.28

33	Peat	11.67	14.13	13.99	14.33	14.25	14.30	11.61	12.84	14.04
34	Penn silt loam	12.00	3.81	4.77	4.03	3.15	5.88	4.29	5.31	4.79
35	Ramona loam	12.09	1.64	2.69	2.20	[a]1.12	1.80	1.68	2.48	1.90
36	Ruston sandy loam	12.04	2.48	3.28	3.20	2.87	2.33	2.82	2.42	2.46
37	St. John's fine sand	12.04	8.29	9.02	7.68	6.97	8.25	8.39	8.97	10.39
38	Sassafras gravelly sandy loam	12.01	2.11	2.39	2.77	2.58	2.37	2.53	2.23	2.66
39	Sassafras silt loam	12.00	4.83	5.50	6.06	5.20	6.28	5.37	6.36	5.06
40	Sharkey clay	12.04	6.86	7.94	7.21	6.75	8.58	8.59	6.96	8.33
41	Summit silt loam	11.99	5.96	6.16	6.31	5.35	6.48	6.30	6.01	5.96
42	Susquehanna clay	12.03	10.58	17.07	12.55	11.44	8.91	11.17	11.05	13.40
43	Tidal Marsh	12.02	15.51	16.58	19.52	17.63	14.13	12.74	13.15	16.28
44	Wabash silt loam	11.61	2.92	4.07	4.72	3.46	3.43	2.77	3.39	3.18
45	Unidentified alkali soil	11.73	9.72	9.06	9.67	9.27	10.61	11.31	9.29	11.17
46	Unidentified sandy loam	12.00	4.00	5.07	4.48	4.38	4.69	4.33	4.81	4.82
47	Unidentified silt loam	12.08	2.27	3.93	2.99	2.81	3.24	2.96	2.77	3.08

[a] Data for 1 specimen only.

TABLE 39.—*Maximum, weighted maximum,[a] and estimated average maximum penetration of 1½-inch wrought ferrous pipe exposed for 12 years.*

[In mils]

Soil No.	Duration of test	Maximum penetration: Open-hearth iron, a	Maximum penetration: Hand-puddled iron, b, d	Maximum penetration: Bessemer steel, e	Maximum penetration: Treated Bessemer steel, y	Estimated average maximum penetration ($n=12$): a, δ[b]	a, $\bar{x}$	a, σ_m[d]	b, d, δ	b, d, $\bar{x}$	b, d, σ_m	e, δ	e, $\bar{x}$	e, σ_m	y, δ	y, $\bar{x}$	y, σ_m
	Years																
1	11.65	93	72	84	68	0	74.3	4.4	0	85.2	5.9	0	71.6	5.8	0	79.5	4.9
2	12.01	[c]56	48	[c]55	80	±3	63.0	6.8	±2	44.9	1.7	±3	54.4	2.6	±3	66.1	6.5
3	12.10	89	81	62	55	0	95.6	7.6	0	77.5	3.2	0	74.4	3.4	0	73.2	2.9
4	12.00	[b]150+	79	79	83	±2	137.3	18.7	−1, ±2	74.7	6.0	±2	71.0	4.5	±2	77.7	7.3
5	12.10	33	51	43	37	±3	38.4	3.3	±2	53.9	4.5	+1, −1, ±2	49.3	2.1	±2	38.3	1.6
[f]6	12.09	23	20	19	18	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7	11.52	52	40	50	[c]29	±4	53.7	6.1	0	37.9	2.0	±4	42.9	3.5	±6	28.1	0.8
8	11.76	100	76	74	58	0	100.9	3.3	0	79.4	4.1	0	73.0	3.2	0	58.8	1.6
[f]9	11.51	43	42	33	52	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10	11.95	50	52	40	39	−2, ±2	0.4	3.8	±3	48.9	2.9	±2	35.2	3.8	±3	37.1	3.6
11	11.92	99	[c]75	71	58	0	80.5	4.1	±1	74.1	3.6	0	75.1	2.9	0	69.6	4.0
12	12.10	61	[c]58	55	[c]59	±3	56.2	4.1	±3	53.4	7.5	±3	50.1	7.2	±4	58.3	5.1
14	11.76	101	109	80	84	0	109.9	8.0	0	111.5	7.8	0	143.0	12.7	0	140.3	9.0
15	12.02	78	50	56	54	±2	78.2	3.9	.....	.....	.....	±2	61.9	3.7	±2	53.8	4.4
16	12.00	82	61	59	63	0	84.0	5.9	0	68.3	5.6	0	70.1	5.5	0	75.5	9.4
17	11.78	41	38	42	39	±4	41.0	1.3	±4	38.1	1.4	±4	41.8	1.4	±4	41.5	2.6
18	11.71	53	42	41	39	0	57.9	3.8	0	51.2	5.1	0	52.4	4.2	0	51.5	4.9
19	11.63	57	62	71	66	0	63.2	3.2	0	54.7	2.7	0	63.5	2.4	0	59.9	2.6
20	11.65	67	49	72	65	0	57.4	4.9	0	59.0	5.1	+1, −1	64.3	9.4	0	57.1	3.1
[g]21	.....	.....	.....	.....	.....	±6	71.7	4.1	±6	48.2	2.8	±6	63.1	2.0	±6	66.4	4.9
22	11.65	73	66	69	78	0	65.0	3.8	0	64.2	1.4	0	66.2	1.8	0	67.4	3.0
[f]23	12.09	145+	145+	145+	145+	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
24	11.95	28	23	21	25	±2	26.3	1.2	±2	21.2	1.0	±2	15.8	1.6	±2	23.1	1.8
25	11.67	[c]52	[c]43	48	32	±3	55.9	3.6	±3	46.7	2.5	±3	47.8	2.3	±2	38.1	1.9
[f]26	11.52	38	47	44	35	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

27	12.02	42	48	61	60	±2	46.6	3.7	{+2, ±2}	49.2	2.4	±2	58.3	7.3	±2	48.5	4.5
28	9.60	145+	132+	137+	145+	±4	174.4	9.6	±4	147.8	8.7	±4	155.2	6.6	±4	146.9	9.8
29	12.04	145+	90	136+	145+	.....	.....	.....	0	99.8	5.3	±1	117.7	8.0	0	121.5	5.7
30	11.62	54	51	59	51	±2	58.4	5.0	±3	50.2	1.2	±2	55.2	3.0	±2	55.5	3.9
31	12.04	34	29	34	31	±2	36.5	2.3	{+1, ±2}	33.9	2.9	{+2, ±2}	36.0	1.3	{+1, ±2}	40.8	5.3
32	11.66	58	43	46	50	0	63.2	5.7	0	50.5	3.4	0	50.2	3.3	0	49.5	2.3
33	11.67	112	98	90	105	±2	145.1	13.1	{+1, −1, ±2}	97.8	2.6	±2	80.9	7.4	±2	108.5	9.3
[f]34	12.00	58	36	41	32	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[f]35	12.09	10	24	18	[e]5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
36	12.04	57	46	49	48	±2	57.0	2.2	±2	53.3	3.3	±2	45.7	2.0	±2	44.8	2.2
37	12.04	76	64	79	68	0	76.1	5.6	0	77.4	6.3	0	94.1	9.0	0	71.6	4.9
[f]38	12.01	35	34	27	30	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
39	12.00	77	57	50	60	0	70.0	8.2	0	49.7	6.8	0	49.5	2.5	0	54.4	3.3
40	12.04	139	68	69	83	0	157.8	15.8	0	86.7	6.7	0	79.7	3.7	0	86.8	4.9
41	11.99	101	95	79	91	±2	106.8	5.3	±2	112.4	12.9	±2	81.0	4.0	±2	85.4	3.4
42	12.03	94	89	111	88	0	95.0	4.3	0	95.2	4.7	0	119.4	6.5	0	95.2	6.1
43	12.02	91	80	100	105	0	95.8	12.1	0	86.9	9.3	0	105.0	12.6	0	114.8	11.6
44	11.61	87	56	63	69	±2	87.7	7.6	±2	56.4	2.3	±2	66.3	2.0	±2	66.3	3.6
45	11.73	82	78	85	82	{+1, −1}	85.1	8.4	+3	51.0	3.3	+2	89.8	8.4	+2	78.5	3.4
[f]46	12.00	49	62	64	104	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
47	12.08	17	46	26	31	±3	19.0	2.8	±2	27.0	3.9	±2	20.7	1.6	±2	19.8	3.0
Average[k]	.....	.....	.....	.....	.....	.....	83.6	2.4	.....	69.1	2.2	.....	75.0	2.2	.....	72.4	2.1

[a] The maximum penetration is the average of the deepest pits on each of 2 specimens. For 1½-inch pipe this has the same value as the weighted maximum penetration.
[b] δ denotes the number of specimens omitted in averaging because of unsatisfactory data. The plus or minus sign of δ denotes whether the pitting of the omitted specimens was more or less than the average. A number in the δ column preceded by a ± indicates the number of specimens for which there is no data.
[c] $\bar{x}$ denotes the average maximum pit depth.
[d] σ_m denotes the standard error of $\bar{x}$.
[e] Data for 1 specimen only.
[f] Data unsatisfactory for determining the pit-depth–time curves.
[g] Specimens lost; average pit depths at the close of 6 years.
[h] A plus (+) indicates that 1 or both specimens were punctured due to corrosion.
[k] Average of the 23 soils, with no deletions because of erratic data.

TABLE 40.—*Maximum, weighted maximum, and estimated average maximum penetration of 3-inch wrought ferrous pipe exposed for 12 years.*

[In mils]

Soil No.	Duration of test	Maximum penetration				Weighted maximum penetration				Estimated average maximum penetration ($n=12$)											
		Open-hearth iron, B, D	Open-hearth steel, K	Bessemer steel, M	Open-hearth steel, Y	B, D	K	M	Y	B, D			K			M			Y		
										δ[a]	$\bar{\bar{x}}$[b]	σ_m[c]	δ	$\bar{\bar{x}}$[b]	σ_m	δ	$\bar{x}$	σ_m	δ	$\bar{\bar{x}}$	σ_m
	Years																				
1	11.65	76	94	[d]101	125	74	91	95	120	+2	75.9	1.9	0	96.7	4.9	±1	93.7	3.7	0	103.0	10.8
2	12.01	56	54	[d]49	67	54	51	46	57	±2	56.6	3.2	±2	55.2	2.0	±3	53.8	2.2	±2	66.4	3.4
3	12.10	76	68	72	84	64	61	69	77	0	73.4	3.2	0	74.5	4.5	0	82.0	3.6	0	85.8	6.4
4	12.00	87	109	84	152	74	103	71	146	±3	89.4	4.0	±3	113.2	10.2	±2	90.0	11.2	+1 −2 ±2	157.3	17.2
5	12.10	44	48	46	49	40	46	43	45	±2	42.5	2.2	±2	68.7	6.3	±2	60.5	4.9	+1 −1 ±1	40.5	12.2
[e]6	12.09	30	14	27	33	26	13	22	29	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7	11.52	47	45	48	49	46	44	46	43	±4	45.1	1.7	±4	44.7	3.2	±4	46.4	3.7	±4	38.3	3.3
8	11.76	83	92	111	127	80	87	68	109	0	77.0	5.2	0	96.0	5.1	0	100.0	5.2	0	130.2	9.2
[e]9	11.51	40	48	49	96	37	46	49	86	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10	11.95	45	52	54	66	40	45	48	53	±2	45.4	3.9	±2	48.1	4.4	±2	62.7	8.6	±2	75.9	9.6
11	11.92	82	71	81	86	71	66	77	74	0	86.2	4.4	0	69.3	1.6	0	84.0	6.4	0	79.4	3.8
12	12.10	75	53	65	[d]85	71	47	63	81	−2 ±3	81.1	6.8	−2 ±3	54.8	4.3	−1 ±3	70.1	2.6	−2 ±4	85.6	2.5
14	11.76	[d]127	83	95	113	117	80	91	109	±1	126.4	5.6	0	91.7	3.7	0	117.3	6.1	0	147.6	11.8
15	12.02	63	83	72	62	58	69	66	59	±2	63.4	6.2	±2	82.2	5.5	±2	68.5	4.5	±2	60.6	1.5
16	12.00	56	87	70	84	55	76	68	77	0	83.5	6.1	0	86.0	2.9	0	75.0	4.6	0	81.9	3.6
17	11.78	42	47	48	42	40	46	45	41	±4	44.3	0.8	±4	47.1	1.0	±4	48.8	2.8	±4	44.6	2.9
18	11.71	41	71	44	45	40	61	42	43	0	65.5	5.3	0	69.5	2.6	0	49.8	3.0	0	56.7	5.5
19	11.63	66	85	60	63	62	78	57	58	0	63.4	3.2	0	80.2	2.0	0	64.3	2.0	0	66.7	2.2
20	11.65	45	81	56	62	44	72	55	57	0	44.8	3.0	0	50.5	4.9	0	53.3	3.1	0	59.2	6.2
21	.....	.....	.....	.....	.....	.....	.....	.....	.....	±6	60.3	7.5	±6	54.3	2.5	±6	64.0	3.3	±6	55.2	2.0
22	11.65	60	56	65	71	56	54	63	65	0	64.2	2.2	0	63.5	1.7	0	65.0	1.7	0	70.8	2.4
23	12.09	150	150	163	[d]177	146	149	145	161	0	156.0	10.0	0	167.1	6.7	0	163.7	5.4	+3 −1 ±1	176.6	10.1

24	11.95	28	29	30	31	26	26	28	30	±2	24.8	2.8	±2	28.5	2.0	−2 ±2	30.5	1.9	±2	36.7	4.2
25	11.67	49	46	57	52	44	42	53	49	±2	51.7	3.0	±2	50.8	3.6	±2	57.6	2.9	±2	53.4	2.8
[e]26	11.52	44	46	38	43	41	44	36	41	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
27	12.02	55	81	83	74	56	76	68	65	±2	58.9	4.5	±2	83.5	5.1	±3	99.3	12.9	±2	76.3	4.6
28	9.60	167	[f]183+	152	216+	160	180	142	216+	±4	169.3	7.1	±4	207.5	11.1	±4	148.6	5.1	±4	221.1	8.9
29	12.04	134	216+	119	[d]216+	117	194	101	171	0	126.4	6.9	0	216.1	10.1	0	142.6	13.1	.....	.....	.....
30	11.62	53	54	63	67	53	51	60	63	±2	60.2	5.7	±2	64.7	7.9	±2	68.4	2.9	±2	61.3	5.1
31	12.04	41	41	40	37	37	39	36	36	±2	43.1	3.8	.....	.....	.....	+2 ±2	40.1	2.5	+2 ±2	40.7	2.7
32	11.66	59	86	62	93	58	81	58	90	0	62.6	5.0	0	65.7	3.7	0	63.3	2.4	0	104.3	10.8
33	11.67	104	108	97	84	99	98	91	79	±2	131.3	14.0	±2	116.3	8.7	±2	114.5	18.9	±2	.....	.....
[e]34	12.00	55	36	50	74	50	35	44	55	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
[e]35	12.09	37	22	69	27	31	19	57	23	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
36	12.04	47	60	45	44	45	59	44	43	±2	48.0	1.2	±2	59.9	2.3	±2	51.9	1.4	±2	47.9	1.9
37	12.04	80	63	95	127	73	60	91	120	0	72.1	4.4	0	67.5	3.0	0	97.5	6.1	0	116.9	8.3
[e]38	12.01	28	22	43	26	26	22	36	22	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
39	12.00	69	69	94	106	60	69	81	98	0	64.2	4.1	0	74.4	8.9	0	69.3	4.4	0	100.0	4.3
40	12.04	69	91	78	75	67	87	70	74	0	70.2	3.2	0	105.4	7.9	0	82.6	5.4	0	82.5	4.5
41	11.99	87	73	75	80	80	71	73	77	±2	86.8	2.8	±2	73.6	3.9	±2	76.8	2.9	±2	78.7	6.0
42	12.03	88	125	92	116	83	124	88	106	0	92.2	25.6	0	124.6	3.9	0	108.2	4.0	0	115.6	4.1
43	12.02	138	128	75	72	131	106	73	68	0	138.4	6.6	0	130.7	9.6	0	102.7	9.1	0	101.5	13.1
44	11.61	65	58	83	75	62	55	77	71	±2	63.8	1.5	±2	62.0	3.5	±2	82.9	3.6	±2	89.4	4.0
45	11.73	85	112	98	124	84	110	93	112	+2	86.2	5.3	+2	111.3	5.8	+2	97.9	7.7	+3	80.5	2.2
[e]46	12.00	77	62	114	80	69	57	113	77	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
47	12.08	34	24	27	26	30	24	27	24	+1 ±2	31.8	3.3	+1 ±3	24.3	2.3	+1 ±2	23.6	1.1	±2	30.6	2.0
Average[g]	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	76.8	2.0	.....	81.1	2.2	.....	78.7	1.5	.....	89.3	1.8

[a] δ denotes the number of specimens omitted in averaging because of unsatisfactory data. The sign of δ denotes whether the pitting of the omitted specimens was more or less than the average. A number in the δ column preceded by a ± sign indicates the number of specimens for which there were no data.
[b] $\bar{x}$ denotes the average maximum pit depth.
[c] σ_m denotes the standard error of $\bar{x}$.
[d] Data for 1 specimen only.
[e] Data unsatisfactory for determining the pit-depth–time curves.
[f] A plus (+) indicates that 1 or both specimens were punctured due to corrosion.
[g] Average of the 23 soils with no deletions because of erratic data.

TABLE 41.—*Loss of weight of wrought pipe exposed for 9 years.*

[In ounces per square foot[a]]

Soil		Wrought iron					Alloy steel				
No.	Type	Hand puddled, A	Mechanically puddled, B	A+B Average	A+B Standard error	Cu-Mo open-hearth iron, H	Low carbon steel, N	2.5% Ni 1.1% Cu, D	5% Cr, P	18% Cr, X	18% Cr 8% Ni, R
53	Cecil clay loam	3.72	3.70	3.71	0.3	3.99	[b]4.09	[b]2.53	[b]2.24	.....	.....
55	Hagerstown loam	3.68	3.78	3.73	.1	[b]3.19	3.82	[b]2.05	1.92	.....	.....
56	Lake Charles clay	[c]22.83	19.54	21.18	.....	[e]18.93	28.76	16.69	23.58	.....	.....
58	Muck	12.57	12.68	12.62	.5	14.51	16.24	[b]6.55	13.88	([d])	0.022
59	Carlisle muck	2.44	2.34	2.39	.4	[b]2.37	4.70	[b]2.61	2.76	.....	.....
60	Rifle peat	[e]14.26	[e]16.48	15.37	4.8	13.68	16.72	[e]10.28	15.55	.....	.....
61	Sharkey clay	6.42	[d]5.66	6.04	0.6	5.56	5.78	[b]3.37	5.10	.....	.....
62	Susquehanna clay	7.80	9.38	8.59	1.1	7.02	6.65	5.42	4.64	0.012	.0029
63	Tidal marsh	[e]8.52	4.24	6.38	1.9	6.33	[e]9.03	7.58	[e]5.85	[e]1.33	([d])
64	Docas clay	[f]16.00+	[f]18.35+	17.18+	.....	[g]D	D	[b c]24.79	D	([d])	.059
65	Chino silt loam	13.60	11.44	12.52	0.9	15.05	[h]12.86	[b]6.00	[b]10.91	.....	.....
66	Mohave fine gravelly loam	[b c]5.82	[b]9.99	7.90	.....	14.60	18.56	[e h]7.54	18.32	.....	.....
67	Cinders	[f]15.21+	D	15.21+	.....	D	[f]58.39+	D	27.92	[e]1.46	.0023

[a] Each ounce per square foot corresponds to an average penetration of 0.0015 inch.
[b] Average loss of weight of the 1939 removals is greater. The maximum loss of weight for the individual specimens of the 1939 removals is greater.
[c] Data for 1 specimen only.
[d] Data cannot be used because of abnormal corrosion due to the presence of asphalt on the ends of the specimen.
[e] Data for the individual specimens differed from the average by more than 50%.
[f] Data for 1 specimen only. The other specimen was destroyed by corrosion.
[g] D, Both specimens destroyed by corrosion.
[h] Average loss of weight of the 1939 removals is greater. The maximum loss of weight for the individual specimens of the 1941 removals is greater.

TABLE 43.—*Average of the relative loss of weight of wrought specimens for four periods of exposure.*

[In percent]

Soil No.	Wrought iron A[a]		Wrought iron B		Cu-Mo iron, H		Low-carbon steel, N		Ni-Cu steel, D		5% Cr steel, P		Average
	Relative loss	Standard error	Relative loss	Standard error	Relative loss	Standard error	Relative loss	Standard error	Relative loss	Standard error	Relative loss	Standard error	
53	62	14	63	14	60	8	62	6	43	8	35	4	54
55	56	9	56	10	45	6	51	8	33	6	26	3	44
56	206	37	179	24	162	31	256	47	133	21	192	46	188
58	153	19	153	22	158	25	176	27	118	18	132	27	148
[b]59	31	2	28	1	33	1	48	3	35	5	34	4	35
60	132	21	137	21	120	19	175	20	117	22	142	39	137
61	78	15	73	14	61	11	62	14	45	4	55	11	62
62	86	3	98	9	86	9	92	10	60	8	56	7	80
63	74	11	56	8	69	4	102	8	59	10	60	5	70
65	167	26	146	13	207	14	192	18	97	18	182	19	165
Average..	104	.....	99	.....	100	.....	122	.....	74	.....	91	.....	.....

[a] See table 7 for the composition of the materials.
[b] Data for only 3 periods of exposure.

TABLE 44.—*Average of the relative maximum penetrations of wrought specimens for four periods of exposure.*

[In percent]

Soil No.	Wrought iron A[a]		Wrought iron B		Cu-Mo iron, H		Low-carbon steel, N		Ni-Cu steel, D		5% Cr steel, P		Average
	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	Relative maximum penetration	Standard error	
53	96	11	103	9	134	9	86	9	56	2	100	11	96
55	108	13	115	15	130	15	93	10	76	5	117	4	106
56	107	15	117	17	128	28	138	31	130	37	207	26	138
58	112	18	117	23	123	30	132	29	103	23	117	9	117
59[b]	37	5	29	3	17	6	43	1	14	5	37	10	30
60	62	6	66	6	54	13	52	18	49	12	110	11	66
61	65	7	68	17	85	24	84	20	53	8	60	14	69
62	106	12	134	23	144	23	126	18	94	11	140	19	124
63	84	17	59	5	101	14	68	12	61	12	144	11	86
65	150	8	158	9	185	29	126	8	98	7	186	8	150
Average..	93	.....	97	.....	110	.....	95	.....	73	.....	122	.....	.....

[a] See table 7 for the composition of the materials.
[b] Data for only 3 periods of exposure.

It should be pointed out that such graphs as figure 13, which are based on the averages of the performances of materials that do not behave the same in different soils, have limited value, as the material that shows the best average performance may not be the best for some specific soil condition.

3. FERROUS-ALLOY SHEETS AND PLATES

For convenience, many of the ferrous alloys submitted in the more recent tests were in the form of sheets or plates. Whether data on plates are applicable to pipes of the same material or not has not been determined. If the plates are laid flat in the trench as most of them were in the Bureau tests, the aeration of the under side may be poorer than that of the upper side. A large part of the specimens show maximum corrosion on the under side.

Table 45 shows the loss of weight and maximum penetration of seven high-chromium-alloy sheets after 9 years of exposure. With the exception of the 12- and 17-percent-chromium materials in three soils, the losses of weight and the pit depths are very small. Comparing the data for the plate K with the pipe R in table 42, which is similar in composition, the pipe lost weight more rapidly in all soils where comparisons can be made. However, the sheets K were placed on edge and were more highly finished. Specimens of the high-alloy sheet buried in soil 64 for 9 years are shown in figure 14. The behavior of these specimens is characteristic of what may be expected of these materials in poorly aerated, corrosive soils.

Materials S and T were included in the test to determine whether or not manganese could be used instead of nickel as an alloying element. The number of specimens is too limited to justify a conclusion regarding this.

It should be pointed out that the notations M and U appearing in table 45 and in some of the following tables may not represent real differences. It is often very difficult to determine whether a specimen is unaffected or whether metal attack has caused an increased roughening of the surface, because the surfaces were rough before burial. In any case, whether the pitting is listed as M or U, the amount of corrosion is negligible.

Tables 46 and 47 show the loss of weight and maximum penetration of alloy steel plates buried 4 years, and table 48 and figure 15 show the relative loss and penetration of the materials in terms of the loss of weight and penetration of open-hearth steel plates for 2 periods of exposure. The data are based on the average performance of 4 plates in each of 14 soils. There are objections to this treatment of data, since the value of the average might be unduly affected by an abnormally large pit depth and because one material might be superior in one soil and correspondingly inferior under some other soil condition. However, examination of tables 46 and 47 shows that these objections are not important with respect to the materials under consideration. Table 48 indicates that the addition of about 4 percent of chromium to an alloy reduces the loss of weight but increases the penetration. This is explained by the postulate that the chromium renders most but not all the surface of the metal more cathodic because of an oxide film which breaks down in a few places. This would result in a large cathodic and a very small anodic area and a high current density and rate of penetration at the small anodes. In many soils the corrosion products are not precipitated on the anode and corrosion is continuous.

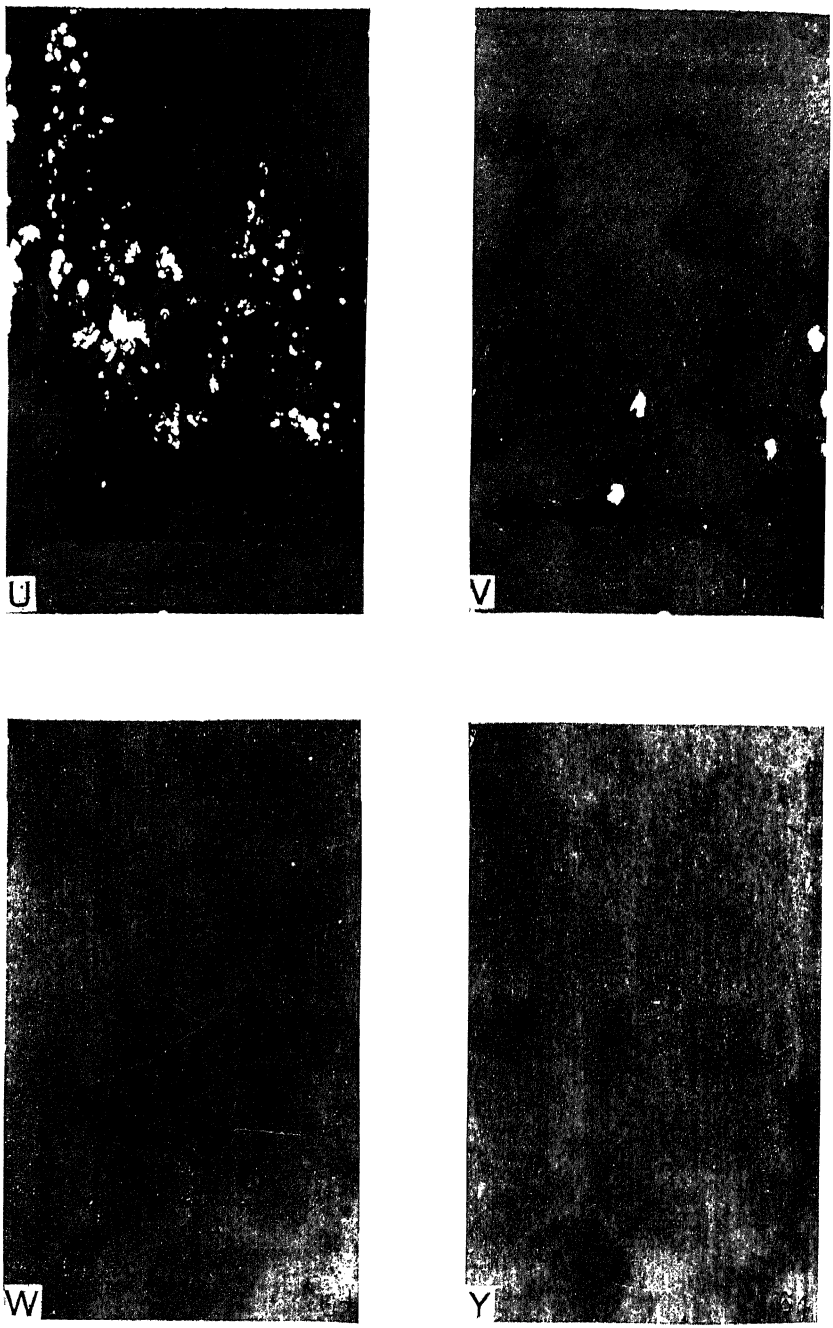

FIGURE 14.—*Specimens of high-alloy sheet buried 9 years in Docas clay at Cholame. Calif. (soil 64).*

U, 12-percent-chromium steel; *V*, 18-percent-chromium; *W*, 18-percent-chromium with 8-percent-nickel; *Y*, 22-percent-chromium steel with nickel and manganese. The white spots on specimens *W* and *Y* are not holes.

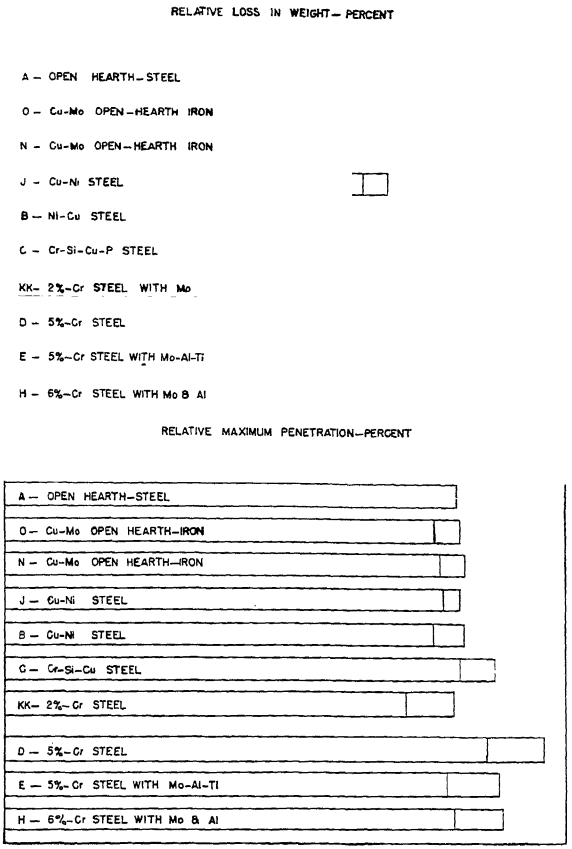

FIGURE 15.—*Relative loss of weight and maximum penetration of ferrous plates for two periods of exposure.*

TABLE 45.—*Average loss of weight and maximum penetration of high-alloy steel sheets exposed for 9 years.*

M, shallow metal attack, roughening of surface, but no definite pitting.
P, definite pitting, but no pits greater than 6 mils.
U, apparently unaffected by corrosion.
+, one or more specimens contained holes because of corrosion, rendering the computation of the exact penetration impossible. The thickness of the specimen has been used as the maximum pit in this case.

Soil No.	(5)[a] 11.95% Cr 0.48% Ni .38% Mn		(5) 17.08% Cr 0.09% Ni .36% Mn		(2) 17.72% Cr 9.44% Mn		(1) 17.76% Cr 3.83% Ni 6.09% Mn		(2) 17.2% Cr 8.95% Ni 0.44% Mn		(5) 18.69% Cr 9.18% Ni 0.36% Mn		(5) 22.68% Cr 12.94% Ni 1.50% Mn	
	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average	Loss, average	Maximum penetration, average
	U		V		S		T		K[b]		W		Y	
	oz/ft²	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
53	.....	.....	.....	.....	.....	.....	.....	.....	0.0010	U	.....	.....	.....	.....
55	0.00042	M	0.0014	U	.....	.....	.....	.....	.....	.....	0.00053	P	0.0015	P
56	.....	.....	.....	.....	.....	.....	.....	.....	[e].110	[e] 25+(5, 7)	.....	.....	.....	.....
58	.....	.....	.....	.....	.....	.....	.....	.....	.0011	U	.....	.....	.....	.....
59	.00084	P	.0016	P	.....	.....	.....	.....	.0014	M	.00074	P	.0021	P
60	[d].0019	[d]P (5, 7)	[f].15	[f]P (5)	.....	.....	.....	.....	.0012	M(5)	.0012	P	.0024	P
61	.....	.....	.....	.....	.....	.....	.....	.....	.0016	P	.....	.....	.....	.....
62	.....	.....	.....	.....	.....	.....	.....	.....	.0011	M	.....	.....	.....	.....
63	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
64	3.17	63+(2, 5, 7)	1.12	63+(2, 5, 7,)	0.48	63+(2, 5, 7)	0.44	[d]P(2, 7)	[f].077	[f] 14+	.0026	P	.0062	P
65	0.040	53+(2, 7)	[f]0.24	[d][f] 43+(2, 5, 7)	.....	.....	.....	.....	.0014	[d] P(2, 7)	.0015	P(2)	.0020	P(2)
66	.56	55+(2, 5, 7)	.70	63+(7)	.....	.....	.....	.....	[f].25	[f] 14+(5, 7)	.00053	M	[f].12	[f] 14+
67	.....	.....	.....	.....	.00066	[d] M(7)	.0042	M	.0015	P	.....	.....	.....	.....

[a] The number in parentheses indicates the number of specimens removed from each test site.
[b] Polished surface.
[c] Data for 1 specimen only
[d] Average loss of weight or pit depth of 1939 removal is greater.
[e] The number in parentheses after the pit depth indicates that at least 1 specimen of a previous removal was punctured, e.g., (2) indicates a puncture after 2 years.
[f] Data for the individual specimens differed from each other by more than 50 percent.

TABLE 46.—*Loss of weight of alloy iron and steel plates exposed for 4 years.*

[In ounces per square foot]

Soil		Exposure	Open-hearth steel,	Open-hearth iron		Low-alloy steel				4 to 6% chromium steel			High-alloy steel, 18% Cr,
				0.45% Cu 0.07% Mo,	0.54% Cu 0.13% Mo,	0.95% Cu 0.52% Ni,	1.01% Cu 1.96% Ni,	Cr-Si-Cu-P steel 1.02% Cr,	2.01% Cr 0.57% Mo,	5.02% Cr,	4.67% Cr 0.51% Mo 0.030% Al 0.022% Ti,	5.76% Cr 0.43% Mo 0.027% Al,	
No.	Type		A	O	N	J	B	C	KK	D	E	H_1	H_2
		Years											
53	Cecil clay loam	4.01	3.23	2.90	3.02	1.32	1.07	2.41	2.18	1.31	1.59	1.44	.....
55	Hagerstown loam	3.90	2.58	2.78	2.73	1.81	1.22	2.33	2.38	1.12	1.19	1.06	.....
56	Lake Charle clay	3.99	18.38	13.79	17.37	19.17	19.52	20.76	14.48	17.93	16.26	14.32	.....
58	Muck	4.01	9.88	9.87	9.36	10.65	11.01	9.03	8.36	5.93	7.16	[a]6.81	[a]0.48
60	Rifle peat	3.98	9.52	7.36	8.22	8.62	9.55	10.23	6.00	6.64	6.23	6.24	.....
61	Sharkey clay	4.01	5.40	5.61	5.65	4.82	3.94	4.59	4.67	1.57	1.81	1.64	.....
62	Susquehanna clay	4.00	3.71	3.62	3.68	3.31	2.94	3.05	2.99	1.22	1.09	1.28	.....
63	Tidal marsh	4.01	[a]6.23	4.70	4.69	3.46	3.44	4.14	3.12	3.80	5.15	5.41	.....
64	Docas clay	3.98	7.44	8.03	[c]6.63	[c]5.95	[c]4.86	5.12	5.39	[c]4.35	5.11	[c]5.03	.....
65	Chino silt loam	3.99	5.26	5.00	5.03	5.00	5.04	5.44	4.53	[c]2.15	[c]2.09	[c]2.17	.....
66	Mohave fine gravelly loam	3.95	[a]16.82	11.65	11.96	10.38	11.38	13.56	12.26	12.13	12.04	14.53	.....
67	Cinders	3.98	34.27	[c]33.22	27.70	35.06	44.29	[c]13.92	[c]16.45	[b]18.09	[bc]11.69	[b]12.88	.....
69	Houghton muck	3.98	4.21	2.86	2.90	2.61	2.37	2.54	2.46	0.86	0.77	0.72	.....
70	Merced silt loam	3.98	10.63	[b]11.02	[b]10.25	[b]7.62	7.80	9.80	9.67	[b]10.04	9.88	10.25	.....

[a] Data for 1 specimen only.
[b] Data for the individual specimens differs from each other by more than 50 percent.
[c] Average loss of weight of the 1939 removals is greater.

TABLE 47.—*Maximum penetration of alloy iron and steel plates exposed for 4 years.*

[In mils]

Soil		Open-hearth steel,	Open-hearth iron		Low-alloy steel				4 to 6% chromium steel			High-alloy steel
No.	Type	A	0.45% Cu 0.07% Mo, O	0.54% Cu 0.13% Mo, N	0.95% Cu 0.52% Ni, J	1.01% Cu 1.96% Ni, B	Cr-Si-Cu-P steel 1.02% Cr, C	2.01% Cr 0.57% Mo, KK	5.02% Cr, D	4.67% Cr 0.51% Mo 0.030% Al 0.022% Ti, E	5.76% Cr 0.43% Mo 0.027% Ti, H_1	18% Cr, H_2
53	Cecil clay loam	76	74	[a]72	57	56	64	52	57	50	57	.....
55	Hagerstown loam	54	44	51	50	52	51	52	48	47	39	.....
56	Lake Charles clay	[b]100	116	100	96	[b]139	[b]77	[b]60	95	[b]80	[b]90	.....
58	Muck	[b]61	[b]48	44	[b]64	[b]52	[b]52	[b]42	[b i]44	[b]46	[b c]44	[c]42
60	Rifle peat	40	28	[a]26	[b]40	28	[b]67	[b]26	[b]51	36	32	.....
61	Sharkey clay	[b]50	66	54	63	[i]56	41	35	36	36	32	.....
62	Susquehanna clay	47	38	49	60	69	44	56	52	46	58	.....
63	Tidal marsh	[c]26	[a]48	47	28	25	41	24	70	73	72	.....
64	Docas clay	78	75	76	84	88	70	70	60	[b]66	72	.....
65	Chino silt loam	51	65	[a]57	60	[a]84	44	[i]55	46	48	56	.....
66	Mohave fine gravelly loam	[c d]188+	84	[i]98	[i]85	73	[b]80	130+	[b]99	88	117	.....
67	Cinders	[a b e]132+	[e f g]55	[b e]74	[b f g]90	[b f g]84	[b]47	[b e]68	[b]57	[b e]52	[b f g]44	.....
69	Houghton muck	22	20	16	15	12	42	27	39	26	33	.....
70	Merced silt loam	[b]77	[a]97	[a]122	82	78	[b]94	[i]94	121	[b h]106	94	.....

[a] Data for the individual specimens differed from each other by more than 50 percent.
[b] Uniform corrosion—impossible to measure true penetration.
[c] Data on 1 specimen only.
[d] +Mark in all cases indicates 1 or more specimens punctured.
[e] Bad corrosion at 1 end.
[f] Plate entirely destroyed at 1 end.
[g] Data for 1 specimen—impossible to obtain data from other specimen because of extreme uniform corrosion.
[h] Hole from both sides.
[i] Average pit depths of the 1939 removals are greater.

TABLE 48.—*Relative loss of weight and maximum penetration of alloy iron and steel plates.*

[Average of two periods of exposure, in percent]

Symbol	Material	Loss of weight			Maximum penetration		
		Average	Standard deviation	Standard error	Average	Standard deviation	Standard error
A	Open-hearth steel	100	.....	.....	100	.....	.....
O	Open-hearth iron—0.45% Cu; 0.07% Mo	100	38	7	101	31	6
N	Open-hearth iron—0.54% Cu; 0.13% Mo	95	19	4	102	35	6
J	Low alloy—0.95% Cu; 0.52% Ni	84	25	5	101	24	4
B	Low alloy—1.01% Cu; 1.96% Ni	83	36	7	102	36	7
C	Low alloy—Cr-Si-Cu-P steel—1.02% Cr	84	19	4	109	45	8
KK	Low alloy—2.01% Cr; 0.57% Mo	78	20	4	100	58	11
D	4 to 6% Cr steel—5.02% Cr	58	27	5	120	70	13
E	4 to 6% Cr steel—4.67% Cr; 0.51% Mo; 0.030% Al; 0.022% Ti	58	24	4	110	66	12
H	4 to 6% Cr steel—5.76% Cr; 0.43% Mo; 0.027% Al	59	26	5	111	61	11

The behavior of the 4- to 6-percent-chromium steel in this test is in agreement with the behavior of the 5-percent chromium-steel specimens in the 9-year test, where lower loss of weight and deeper pitting was observed in comparison to plain steel.

Further inspection of figure 15 shows that the nickel-copper steel (B) is no better than some of the other low-alloy steels with respect to loss of weight and pitting. This is contrary to the results of the 9-year specimens, where the nickel-copper specimens of approximately the same composition appeared to be somewhat better than the other specimens. It should be noted that the scale on the 9-year nickel-copper steel specimens was removed, whereas the 4-year specimens were coated with a hard, uniform layer of mill scale. The acceleration of pitting resulting from local failure of the oxide coating would account for the relatively poor performance of the 4-year nickel-copper specimen (B), as compared with the 9-year specimen (D) of the same composition.

Figures 16 and 17 show the low-alloy plates exposed to soil 70. Areas where the mill scale was left intact on the nickel-copper (B) and the copper-nickel (J) steels are clearly shown.

Table 49 shows the averages of the loss of weight and maximum penetrations for a low-alloy plate and pipe and two high-alloy plates buried approximately 2-years. Although the loss of weight and depth of maximum penetration of the two high-alloy materials is slight, there is a consistent difference favoring the higher alloy. It is too soon to reach definite conclusions as to the relative merits of the copper-molybdenum steel and the chromium-molybdenum steel. The reader is cautioned against comparing these data with data for other materials exposed for the same length of time but buried at an earlier or later date, as two periods equal in length may differ considerably in amount or distribution of rainfall. For longer periods of exposure these differences will be of less importance.

4. BOLTS

Users of mechanical joints for pipes have frequently found severe corrosion of the bolts used, especially at the threaded ends. This led to the inclusion of a variety of bolts in the tests, some of which connected pieces of cast iron when buried, whereas others were completely exposed

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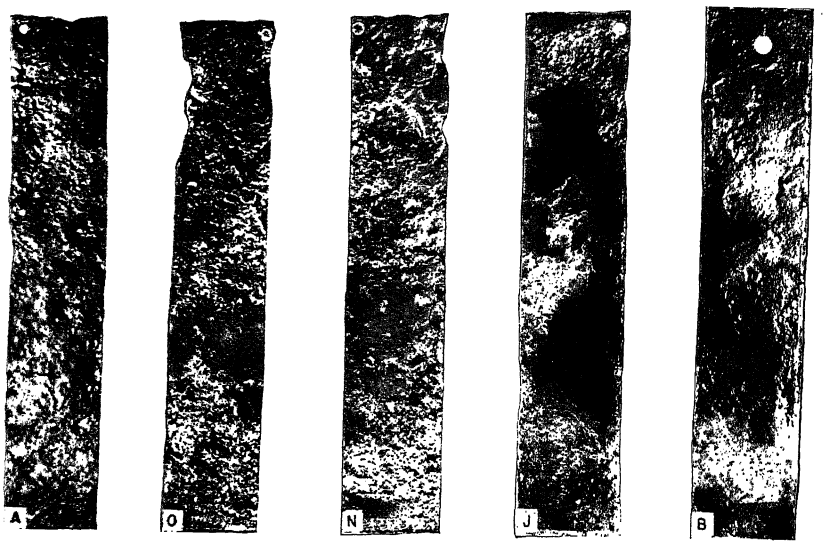

FIGURE 16.—*Ferrous plates exposed 4 years to Merced silt loam at Buttonwillow, Calif.*

See table 7 for the composition of the specimens.

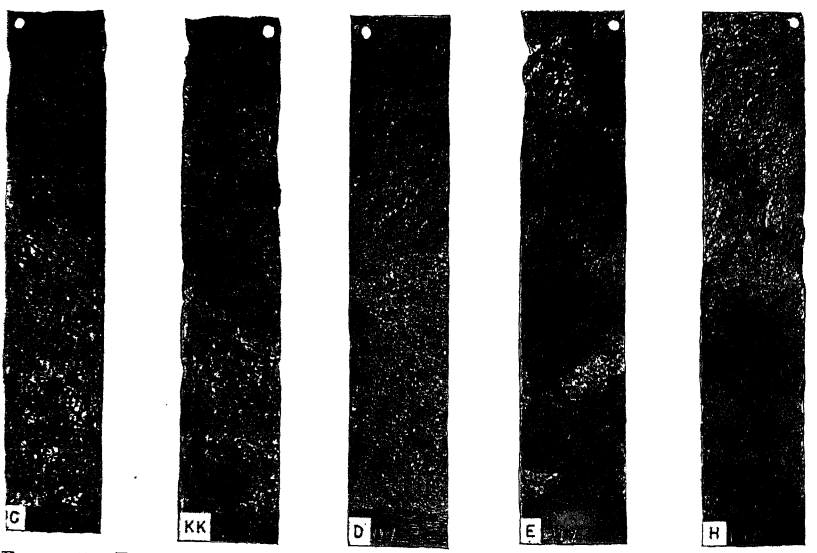

FIGURE 7.—*Ferrous plates exposed 4 years to Merced silt loam at Buttonwillow, Calif.*

See table 7 for the composition of the specimens.

to soil. None were under severe stress. The irregular shapes of the bolts, their partial protection by the nuts and the materials which they held together, the galvanic couples involved, and the relatively few specimens of each material subjected to the same conditions resulted in quite unsatisfactory data, some of which however, are presented in table 50. The pit-depth measurements were limited to the heads of the bolts because it was impracticable to measure the pits on the body of the bolt ac-

curately. The data indicate little difference in the performance of the different varieties of bolts. Sherardized bolts, and to a less extent lead-coated bolts were more corrosion resistant than corresponding steel bolts, which, incidentally, were submitted as wrought-iron bolts.

TABLE 49.—*Loss of weight and depth of maximum penetration of low-alloy and high-alloy steel specimens exposed for 2 years.*

U, apparently unaffected by corrosion.
M, shallow metal attack, roughening of the surface but no definite pitting.
P, definite pitting but no pits on either specimen greater than 6 mils.

Soil		Exposure	.05% Cu, .07% Mo open-hearth iron (plate), MM		2% Cr steel with .49% Mo (pipe), NN		20% Cr, 22% Ni steel (plate), DT		18% Cr, 11% Ni steel (plate), CM	
No.	Type		Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration
		Years	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
53	Cecil clay loam	1.91	[a] 2.32	[a] 42	1.97	65	0.0048	U	0.0054	M
55	Hagerstown loam	2.03	0.92	44	0.92	59	.0065	U	.0061	M
56	Lake Charles clay	1.91	11.16	60	13.81	78	.0033	U	.0067	M
58	Muck	1.91	4.70	48	5.88	46	.0017	U	.0053	P
60	Rifle peat	1.91	3.44	16	4.08	18	.0017	U	.0038	P
61	Sharkey clay	1.92	2.32	41	1.98	42	.0032	U	.0063	U
62	Susquehanna clay	1.90	2.96	40	2.57	40	.0020	U	.0074	P
63	Tidal marsh	1.88	2.08	22	1.76	38	.0046	U	[b] .0084	[b] M
64	Docas clay	1.90	4.09	47	3.92	40	.0018	U	.0063	M
65	Chino silt loam	1.91	[a] 3.14	[a] 43	3.87	51	.0048	U	.0067	M
66	Mohave fine gravelly loam	1.86	6.64	71	9.02	[c] 145+	.0041	U	.0095	P
67	Cinders	1.90	25.97	128	17.75	124+	.0042	U	.0056	U
69	Houghton muck	1.90	[a] 2.25	[a] 13	1.89	22	.0018	U	.0060	U
70	Merced silt loam	1.90	10.07	92	12.81	130+	.0035	U	.0078	M

[a] Data for 1 specimen only.
[b] Data for 3 specimens.
[c] +Indicates that 1 or both specimens contained holes due to corrosion.

5. EFFECT OF CORROSION ON BURSTING STRENGTH

The users of low-pressure pipe have frequently found on uncovering a pipe to repair one leak that punctures existed in several other places, some of which did not leak until the corrosion products were removed. If soil conditions are such that the corrosion products are deposited on the corroding areas, these products may form plugs of sufficient strength to prevent leaks until corrosion has weakened a considerable part of the pipe wall. This is shown by the following tests. A set of corrosion specimens, which included four pieces of 6-inch cast iron, were buried in Imperial clay near Niland, Calif. (soil 113). When the specimens were removed after an exposure of about 6 years, two of the cast-iron specimens were so corroded that they broke while being cleaned. The maximum pit depths in the other two were 0.243 and 0.345 inch, respectively. At the beginning of the test, a 36-inch length of 6-inch cast-iron pipe with the ends closed was filled with water and buried at the end of the trench. A small copper tube was brought out from the end of the pipe, by means of which hydraulic pressures have been applied to the pipe at 2-year intervals. Fifteen years after the pipe was buried it withstood a pressure of 400 pounds per square inch. A similar test has been conducted in Merced silt loam and in a muck soil in New Orleans similar to the soil at site 29 and in Houston black clay (soil 15) with similar results. In 1940, similar tests on standard and light weight

TABLE 50.—*Corrosion of ¾-inch bolts.*

Soil No.	Soil type	Malleable-iron bolts (4 inches long)						High strength, C[a]		Steel bolts, D[b]	
		Number of specimens of each kind	Duration of test	Decarburized, A[a]		Not decarburized, B[a]					
				Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration
			Years	*Grams*	*Mils*	*Grams*	*Mils*	*Grams*	*Mils*	*Grams*	*Mils*
55	Hagerstown loam	2	9.11	5.26	65	5.11	46	7.89	76	5.56	42
56	Carlisle muck	2	9.12	7.46	20	5.89	12	6.57	26	6.00	12
61	Sharkey clay	2	9.53	9.95	51	11.08	43	5.25	29	5.18	20
62	Susquehanna clay	2	9.47	8.05	58	8.93	70	9.74	58	8.10	54
	Average	.....	.....	7.68	48	7.75	43	7.35	47	6.21	32

Coated steel bolts and nuts (3-inches long)

Soil No.	Soil type	Number of specimens of each kind	Duration of test	Total loss of weight					
				Sherardized steel, G		Lead-coated steel, F		Steel, D[b]	
				Bolt	Nut	Bolt	Nut	Bolt	Nut
			Years	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*
13	Hanford very fine sandy loam	4	10.16	3.20	1.23	6.50	2.02	24.99	8.43
24	Merrimac gravelly sandy loam	4	10.63	2.37	0.90	1.43	0.78	3.04	1.29
28	Montezuma clay adobe	1	9.60	19.32	8.63	.....	.....	29.11	13.60
29	Muck	4	10.08	13.45	4.60	18.93	7.92	23.63	9.45
42	Susquehanna clay	3	10.05	4.47	1.80	6.52	2.62	15.30	5.41
43	Tidal marsh	4	10.73	24.32	8.05	13.05	7.54	37.52	5.47
45	Unidentified alkali soil	4	10.55	15.19	8.09	42.23	14.40	16.71	5.60
	Average	.....	.....	11.76	4.76	14.78	5.88	21.47	7.04

[a] On head of bolt only.
[b] Included for comparison.

steel pipe were started. The light weight pipe blew out in 1943 at three sites at pressures of 151 pounds or less, but the standard-weight pipes withstood a pressure of 400 pounds per square inch. These tests indicate that corrosion products tend to plug the small-diameter pits and thus to render the pipes serviceable in spite of severe local corrosion. However, too much reliance should not be placed on the strength of corrosion products. If large areas are corroded deeply, or if the pipes are subject to severe water hammer or vibration, breaks or leaks may develop.

A somewhat different but related study of the effects of pitting has been made by a manufacturer of wrought pipe [58]. A number of lengths of steel pipe used underground and pitted by corrosion were cleaned. Heads were welded on the ends and hydraulic pressure applied until the pipes burst. The report concludes that the results of these tests indicate by a comparison of the actual bursting strength with the calculated theoretical bursting strength, that although the reduction in bursting strength of any given size and wall thickness depends upon the extent to which corrosion has occurred and the depth of the pits, it is significant that a single or a dozen or more widely scattered pits of varying depths up to one-half or more of the original wall thickness does not impair the bursting strength and usefulness of the pipe to any marked degree, as the surrounding wall supports the base of the pit and prevents the pipe from bursting, except at high pressures, that is, pressures many times the normal working pressure of the average water line.

It will be noted that the report [58] deals with the supporting strength of adjacent metal and unpunctured pipe from which the products of corrosion have been removed. No doubt, the tests first reported in this section were affected by the same factor, but it is probable that at some of the test sites corrosion has punctured the pipe wall, as specimens which have been similarly exposed, removed, and cleaned have been punctured after much shorter periods of exposure.

VI. INTERPRETATION OF RESULTS ON FERROUS MATERIALS

1. GENERAL CONSIDERATIONS

In interpreting the data obtained in the National Bureau of Standards soil-corrosion investigation, the reader should keep in mind the fact that the original purpose of the investigation was to determine the extent to which soils are corrosive with respect to metals commonly placed in them, in the absence of electric currents from street railways or other sources of power. It should also be understood that many of the phenomena related to the behavior of metals underground were not generally understood at the time the tests were undertaken. The results of the tests have been entirely satisfactory as far as the original limited objectives are concerned. Furthermore, certain more extensive inferences can be drawn from the data, provided always that the specific conditions under which the tests were carried out are given due consideration. Care should be taken, however, to guard against adopting too far-reaching conclusions from too limited data. It should also be emphasized that predictions based upon the behavior of individual test specimens cannot be relied upon with certainty except for similar materials operating under identical conditions. The performance of two specimens of the same material exposed to nominally the same conditions may differ considerably owing

to unknown differences in material or environment. For this reason, it should be fairly obvious that general conclusions should be based on the average performance of a considerable number of specimens exposed to the same soils under as nearly identical conditions as possible.

Several factors that affect the corrosion of metal underground have already been mentioned, including depth of burial, scale on the surface, diameter and area of pipe, and duration of exposure. To these should be added the roughness and degree of oxidation of the surface, the condition of the soil at the time of burial, and other factors that may be peculiar to a given location.

The data on loss of weight and pit depths shown in the foregoing tables give a fairly clear picture of the corrosion of the specimens used in the tests, and give a good indication of the extent to which corrosion occurs in the various soils. Also, by employing one or more of the empirical formulas already discussed, the progress of corrosion can be expressed. The accuracy to which a given equation represents the actual course of the corrosion process depends upon the dispersion of the data as indicated by the standard errors, which in turn depend upon the number of observations and their accuracy. If it is desired to make predictions of the performance of a pipe line buried in a given soil, it will be necessary to employ some method of extrapolation. It should be understood that extensive extrapolation is a somewhat hazardous procedure at best, especially with respect to corrosion phenomena, as it involves not only the extension of areas and time of exposure, the effects of which can be approximately expressed mathematically, but also of changes in environment which cannot be so expressed. However, as the environmental changes tend to counteract each other, statistical treatment of the data results in a fairly reliable determination of what may be expected on the average. What will happen in a single exposure is practically unpredictable. The standard error of the predicted result is a measure of the reliability of the prediction and should always be considered along with the prediction.

2. EXTRAPOLATION OF DATA

Any of the equations for the relation between pit depth and time may be combined with any of the equations representing the relation between pit depth and area. The choice of which equations should be combined depends somewhat on the ease with which the resulting equation can be applied to the data at hand and on the precision desired for the calculations. Although the use of different equations will yield different results, in many cases the standard errors of the differences resulting from the application of different equations to a set of data indicate that the differences in the results may not be significant. When the extrapolations by means of different equations are small, the differences in the results are often not very important. When the extrapolations are large, the standard errors of the results are large, and large apparent differences are therefore to be expected. The equations should be regarded as means for roughly estimating the corrosivity of soils and for this purpose are very useful. In every case the standard error of the estimate should be computed in order to give an indication of its reliability.

For the purpose of illustration, Ewing's pit-depth–time equation has been combined with Scott's and with Ewing's pit-depth–area equations. This gives the equations

$$P=kT^nA^a \text{ and } P=kT^n\ (C \log A+1),$$

in which P is the pit depth on an area, A, at any time, T, and C, a, k, and n are constants derived from an analysis of the data on pit depths. Table 51 gives the values of these constants for 47 soils. By means of the equations given above, the average depth of the deepest pits on 1,000 linear feet of 8-inch pipe exposed 30 years were calculated. By rearrangement of the equations, it was possible to calculate the average length of pipe associated with a puncture in 30 years and the time required for an average of one puncture of the pipe wall per 1,000 feet of pipe. These values are also shown in table 51. As the data for pure open-hearth iron, wrought iron, Bessemer steel, open-hearth steel, and open-hearth steel containing 0.2 percent of copper were not definitely different, they were averaged for the calculation of the constants in table 51. The data for cast iron were more erratic and were not used on this account.

The values of $k_{5.3}$, column 5, are the averages of maximum pit depth on specimens having areas of 0.4 square foot. Their exposure was 5.3 years. The values of $k_{5.3}$ range between 21 and 107 mils. The values of the area factor, a, column 3, range from 0.08 to 0.32. The values of the time factor, n, column 7, range between 0 and 0.92.

Attention is called to the values of k, a, and n in order that the reader may realize how greatly soils differ, and also to the standard errors of these values so that he can see the erratic nature of soil corrosion, even under conditions that are somewhat less diverse than those frequently encountered by pipe lines.

In columns 11 and 15 of table 51 are shown the computed averages of the maximum pit depth to be expected on a group of 8-inch pipes 1,000 feet long and 30 years old. The standard errors in columns 12 and 16 are a measure of the variations that may be expected from the listed pit depths. The standard errors (σ_p) for the pit depths derived by Scott's equation are computed by means of the equation

$$\left(\frac{\sigma_p}{P}\right)^2=(2.3\sigma_a\log A)^2+(2.3\sigma^n\log T)^2+\left(\frac{\sigma_k}{k}\right)^2.$$

The standard errors for the pit depth derived by Ewing's equation were calculated from the equation

$$\frac{\sigma_p}{P}=\left(\frac{\sigma_c\log A}{C\log A+1}\right)^2+(2.3\sigma_n\log T)^2+\left(\frac{\sigma_k}{k}\right)^2.$$

In these equations σ is the standard error of the quantity indicated by the subscript. The other letters have the same significance as in the other equations. In table 51 the unit of area is 0.4 square foot and the unit of time is 5.3 years. The large values of the standard errors of P show that columns 11 and 15 indicate only the order of magnitude of the pit depths to be expected under the assumed conditions.

Columns 13 and 17 show the computed average length per puncture for a 30-year-old 8-inch pipe line having a wall thickness of 0.322 inch. Columns 14 and 18 show the estimated time required for the development of an average of one leak per 1,000 feet on 8-inch pipes having a wall thickness of 0.322 inch. It can be shown that if the extrapolation of the pit-depth data is large with respect to either the area exposed or the period of exposure, the standard error of the estimate is correspondingly large. As many of the computed lengths and times are very long, their standard errors are very great, and consequently they indicate only that the corresponding soils are not very corrosive.

TABLE 51.—*Calculated data on pit depths and leaks on a pipe line.*

[Length of unit section 1,000 feet, diameter of pipe 8.625 inches, thickness of pipe wall 322 mils]

Soil		Constants								Scott's pit-depth-area equation				Ewing's pit-depth-area equation			
No.	Type	a	σ_{-a}	$k_{5.3}$	$\sigma k_{5.3}$	n	σ_m	$C_{.4}$	$\sigma c_{.4}$	Deepest pit in 30 years	Standard error	Length of pipe per puncture in 30 years	Time for puncture per 1,000 feet of pipe	Deepest pit in 30 years	Standard error	Length of pipe per puncture in 30 years	Time for puncture per 1,000 feet of pipe
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
										Mils	*Mils*	*Feet*	*Years*	*Mils*	*Mils*	*Feet*	*Years*
1	Allis silt loam	0.146	0.021	58.5	2.7	0.49	0.06	0.417	0.069	475	103	6.2×10	13	351	53	3.1×10^{2}	25
2	Bell clay	.131	.030	45.4	2.2	.34	.08	.370	.099	254	76	6.1×10^{3}	60	195	42	1.6×10^{7}	130
3	Cecil clay loam	.144	.024	68.8	2.3	.17	.05	.413	.082	320	73	1.0×10^{3}	31	235	36	1.9×10^{5}	190
4	Chester loam	.160	.020	51.6	6.4	.59	.17	.459	.068	572	208	2.7×10	11	390	130	9.1×10	22
5	Dublin clay adobe	.144	.030	37.0	3.0	.47	.13	.407	.106	290	102	2.0×10^{3}	37	211	61	1.8×10^{6}	74
6	Everett gravelly sandy loam	.144	.028	21.7	1.1	0	.05	.409	.092	75	20	2.4×10^{7}	∞	55	9	∞	∞
7	Maddox silt loam	.116	.009	31.1	2.0	.46	.07	.309	.026	188	30	1.0×10^{5}	97	149	22	1.3×10^{11}	160
8	Fargo clay loam	.133	.009	64.4	0.9	.32	.07	.365	.032	353	51	4.9×10^{2}	22	266	35	2.4×10^{4}	55
9	Genesee silt loam	.172	.028	44.0	5.4	.16	.15	.511	.107	97	97	3.7×10^{3}	120	169	54	1.4×10^{8}	1,700
10	Gloucester sandy loam	.184	.027	37.2	3.2	.42	.13	.553	.099	378	127	4.2×10^{2}	20	237	64	1.0×10^{5}	62
11	Hagerstown loam	.140	.021	62.9	2.7	.32	.06	.396	.071	367	78	3.9×10^{2}	20	272	42	1.4×10^{4}	51
12	Hanford fine sandy loam	.140	.031	51.2	14.0	.13	.73	.398	.109	215	284	1.7×10^{4}	670	159	208	2.4×10^{9}	6,500
13	Hanford very fine sandy loam	.193	.015	63.7	7.8	.18	.20	.573	.055	465	181	1.6×10^{2}	4	275	100	8.8×10^{3}	74
14	Hempstead silt loam	.158	.033	85.5	4.5	.48	.07	.472	.123	770	241	4.0	5	545	116	4.0	10
15	Houston black clay	.100	.015	51.4	3.6	.32	.11	.265	.044	212	155	6.4×10^{4}	110	178	39	1.2×10^{9}	190
16	Kalmia fine sandy loam	.118	.017	66.0	3.7	.32	.13	.320	.053	319	88	1.0×10^{3}	31	252	63	7.8×10^{4}	64
17	Keyport loam	.125	.038	33.1	1.9	.19	.07	.360	.123	136	48	1.0×10^{6}	2,900	108	26	8.7×10^{15}	9,400
18	Knox silt loam	.111	.018	46.0	5.8	.18	.12	.301	.053	164	47	4.4×10^{5}	1,300	134	35	8.2×10^{12}	4,000
19	Lindley Clay loam	.103	.010	51.9	1.6	.34	.04	.270	.026	226	28	2.8×10^{4}	83	188	17	2.0×10^{8}	140
20	Mahoning silt loam	.188	.038	34.7	3.0	.43	.10	.584	.131	371	120	4.7×10^{2}	22	234	58	1.2×10^{5}	63
21	Marshall silt loam	.129	.012	55.7	3.1	.60	.07	.351	.033	480	81	4.5×10	15	364	52	1.7×10^{2}	24
22	Memphis silt loam	.082	.009	57.7	1.1	.21	.03	.212	.024	169	16	2.7×10^{6}	650	149	11	6.9×10^{12}	1,200
23	Merced silt loam	.139	.044	107.3	2.9	.51	.04	.391	.140	863	334	0.8	4	640	144	0.7	8
24	Merrimac gravelly sandy loam	.172	.035	22.7	1.6	.11	.09	.515	.128	121	42	2.9×10^{5}	2.1×10^{5}	80	19	1.1×10^{20}	8.8×10^{6}
25	Miami clay loam	.088	.008	40.8	2.0	.29	.06	.227	.026	144	19	9.2×10^{6}	480	125	16	7.7×10^{15}	780

26	Miami silt loam	.120	.028	45.7	7.1	.41	.22	.336	.091	262	125	5.5×10^{3}	49	211	93	3.6×10^{6}	85
27	Miller clay	.170	.037	38.1	1.6	.65	.08	.511	.130	511	179	6.6	15	343	76	4.4×10^{2}	27
28	Montezuma clay adobe	.106	.005	86.0	13.2	.92	.22	.277	.041	1,059	437	0.01	8	865	362	0.02	10
29	Muck	.178	.043	92.0	2.0	.60	.03	.538	.152	1,211	455	0.6	3	783	154	.50	7
30	Muscatine silt loam	.123	.033	32.1	7.0	.53	.26	.351	.112	233	139	1.3×10^{4}	55	187	100	6×10^{7}	84
31	Norfolk	.172	.027	40.4	2.0	0	.08	.508	.095	179	49	3.0×10^{4}	∞	117	22	9.1×10^{12}	∞
32	Ontario loam	.165	.039	44.8	2.6	.33	.07	.502	.138	330	120	8.6×10^{2}	28	229	51	2.2×10^{5}	84
33	Peat	.168	.028	56.4	7.1	.74	.16	.500	.109	868	338	2.7	8	585	197	2.6	13
34	Penn silt loam	.157	.012	41.0	5.4	.54	.18	.447	.042	406	144	2.3×10^{2}	19	280	96	7.9×10^{3}	39
35	Ramona loam	.318	.067	26.5	1.3	.25	.08	1.227	.321	638	381	1.2×10^{2}	2	229	60	7.3×10^{4}	120
36	Ruston sandy loam	.097	.014	45.4	0.9	.14	.03	.255	.041	134	20	8.6×10^{6}	1.5×10^{4}	114	11	1.2×10^{17}	5.2×10^{4}
37	St. Johns fine sand	.191	.017	65.4	3.7	.27	.09	.570	.063	544	121	6.4×10	4	328	60	7.8×10^{2}	28
38	Sassfras gravelly sandy loam	.153	.028	27.5	0.4	.23	.02	.443	.095	154	38	1.2×10^{5}	750	109	15	5.6×10^{14}	3.3×10^{3}
39	Sassafras silt loam	.150	.015	47.4	2.4	.51	.07	.424	.051	419	78	1.7×10^{2}	18	297	45	3.2×10^{3}	35
40	Sharkey clay	.144	.019	60.9	3.9	.50	.10	.405	.064	503	124	4.5×10	12	365	76	1.8×10^{2}	23
41	Summit silt loam	.095	.018	54.8	3.9	.39	.20	.252	.055	245	95	1.7×10^{4}	61	210	78	1.3×10^{7}	90
42	Susquehanna clay	.098	.009	84.7	0.4	.30	.006	.256	.026	332	26	7.3×10^{2}	27	279	14	1.5×10^{4}	48
43	Tidal marsh	.195	.023	83.2	4.0	.47	.06	.590	.081	1,013	274	2.8	3	605	90	2.8	17
44	Wabash silt loam	.148	.038	58.5	0.4	.30	.009	.440	.140	353	116	5.3×10^{2}	22	260	52	2.6×10^{4}	60
45	Unidentified alkali soil	.142	.025	54.3	6.8	.78	.16	.406	.084	716	260	3.6	11	530	174	3.6	16
46	Unidentified sandy loam	.186	.011	79.3	4.4	.18	.08	.545	.040	540	96	6.2×10	2	331	52	7.1×10^{2}	26
47	Unidentified silt loam	.237	.030	20.7	1.4	.30	.09	.762	.120	270	84	2.1×10^{3}	54	134	28	1.2×10^{10}	550

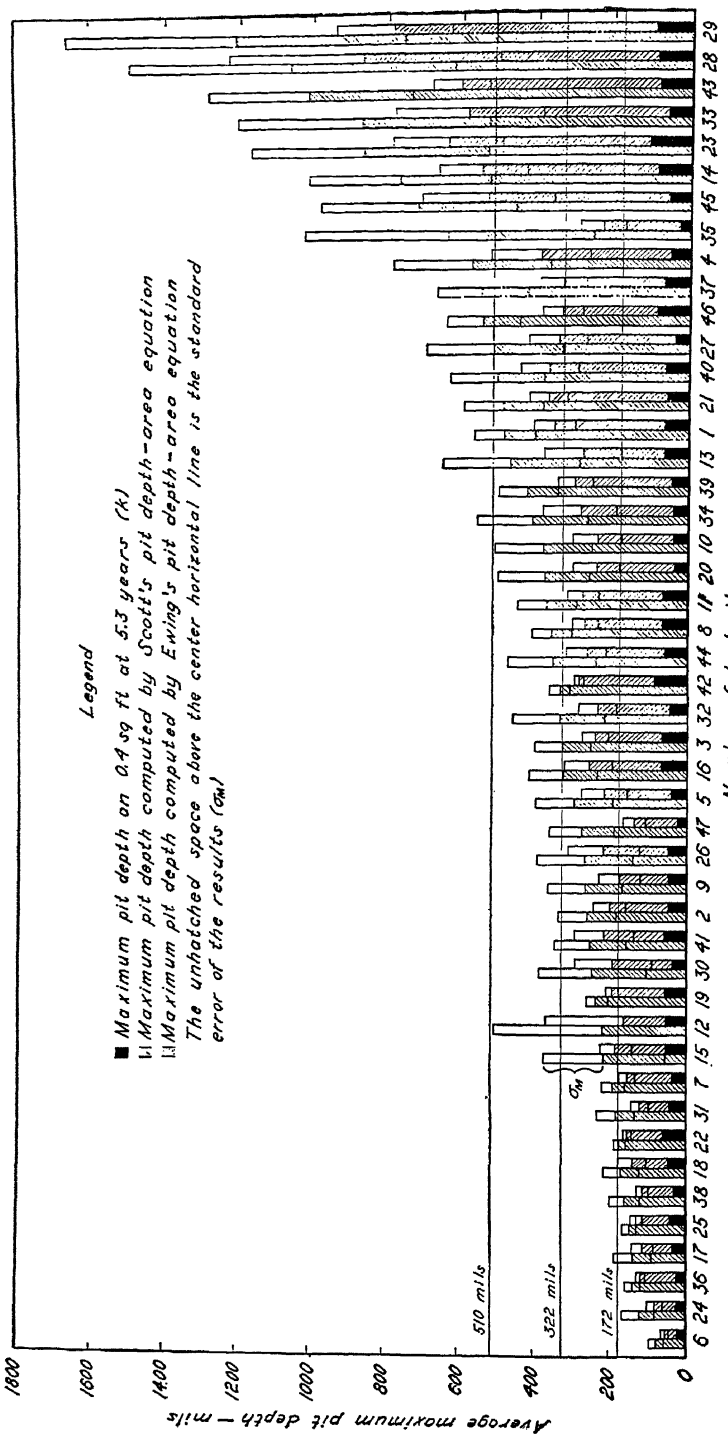

FIGURE 18.—*Estimated maximum pit depth on 1,000 feet of 30-year-old 8-inch pipe.*

Figure 18 which is plotted from data in table 51, shows graphically the estimated maximum depth of pit on 1,000 feet of 30-year-old 8-inch pipe and the standard errors of the estimates. The standard errors of the predictions are such that in most cases the values predicted by one equation fall within the averages predicted by the other, plus or minus once or twice its standard error. For smaller extrapolations, the results obtained by the two equations would of course differ less.

Although the data in table 51 must be recognized as rough approximations, they are of use to those interested in selecting the proper thickness for a pipe wall or in determining whether or not a protective coating should be applied.

The relative depth of pits on pipes in different soils varies with the area of the exposed material and with the period of exposure. If the data in column 5 are compared with those in columns 14 and 18, it will be seen that although after 5 years of exposure the specimens in Cecil clay loam, soil 3, were pitted more deeply than those in Chester loam, soil 4, a pipe in the first-named soil would last much longer than one in the other soil.

One hundred seventy-two mils has been suggested [59] as the permissible thickness for 8-inch water-supply pipe for pressures up to 250 pounds per square inch. An examination of column 11 indicates that within 30 years such an unprotected pipe would average at least one puncture per 1,000 feet in 38 of the 47 soils. According to column 15. punctures on the same length would occur in 34 of the 47 soils. A good protective coating would of course reduce the number of punctures. As supply lines frequently are readily accessible, the cost of repairing them may not be great, and it is quite possible that the cost of repairs would be less than the cost of a protective coating or of thicker pipe. The table therefore does not indicate that light-weight pipe would be unsatisfactory. Column 15 indicates that standard-weight steel pipe (0.322 in.) would develop a puncture in 14 soils and class B cast-iron pipe (0.51 in.) in 7 soils under the same conditions.

It already has been said that Ewing's pit-depth–area equation probably represents available data somewhat better than Scott's. Table 51 shows that Ewing's equation results in the prediction of shallower pits, fewer leaks, and longer pipe life.

The standard errors for the estimates of pit depths on 1,000 feet of pipe at 30 years are so large, however, they indicate that the estimated depths are quite uncertain. It probably would be desirable to recompute the estimates on some basis involving less extrapolation. One engineer limits his extrapolation to 40 feet of pipe.

3. LIFE OF PIPE

The expression "life of pipe" should be avoided because it has no generally accepted meaning, although the term is frequently used. By making a sufficient number of repairs, a pipe may be made to last indefinitely, although it might be more economical to replace it. Figures 19, 20, and 21 illustrate different types of repairs to steel pipe lines. Usually a pipe-line operator repairs or replaces badly corroded sections of his lines before leaks occur and so adjusts his reconditioning program that the number of leaks on his lines does not increase with the age of the line. Under such a policy, the life of a pipe line is the time there is need for the service.

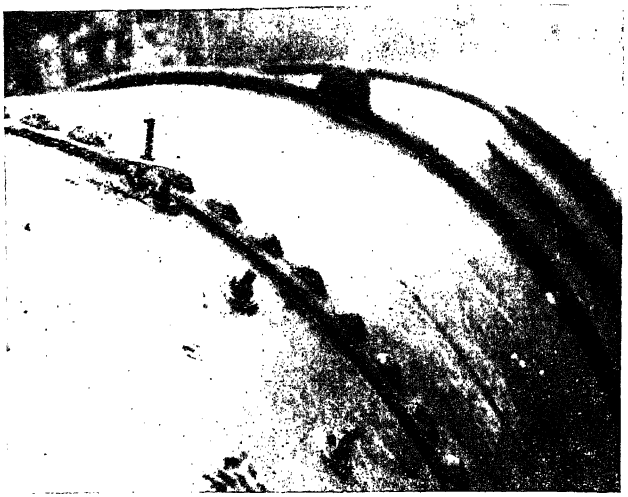

FIGURE 19.—*Three types of repairs on a water line.*
Bolts and washers used to close holes in large diameter steel pipe. Note also corrosion of rivet heads and bands used to hold patches.

Obsolescence rather than corrosion usually determines the time a pipe line remains in service, and the time required for a section of pipe to be punctured usually does not determine the time the pipe section will remain in service. This is a function not only of the depth of the deepest pit but of the number and depth of the other pits and the relative cost of repairs and replacement.

If by "life of pipe" is meant the average time required for corrosion to puncture a pipe wall, the answer is that it depends on the soil, the thickness of the pipe wall, and the area exposed, and the life of ferrous pipe can be estimated by means of the equations presented in the preceding pages. The life of a single section of pipe like that of an individual person cannot be predicted with any degree of assurance.

4. COMPARISON OF TEST DATA WITH DATA ON PERFORMANCE

Much has been said about the value of experience in estimating the corrosivity of soils. It is difficult, however, to express experience in sufficiently quantitative terms to make the information usable in the way that the results of tests are used, because the conditions under which the data of experience are obtained are often poorly defined, and because observations of identical conditions are usually not numerous enough to permit an estimate of the standard error or reproducibility of the experience. When experiences are analyzed, it is often difficult to determine their exact significance or their applicability to some different condition. Experiences are frequently contradictory and may be the results of some unrecognized conditions. They should, therefore, be examined carefully if they are to be applied to new construction.

As the National Bureau of Standards soil-corrosion tests were conducted with the cooperation of operators of pipe lines who furnished the test sites and local labor, it might be assumed that a comparison of the Bureau's data with the field experience of the cooperators would furnish a key to the application of the results of the test to pipe-line corrosion. When such a comparison is attempted, however, a number of

difficulties are encountered. Although there are pipes in the vicinities of most of the test sites, their extent in the soils of the test sites can be determined only by extensive soil surveys. Most of the pipe lines originally carried some kind of protective coating. In many cases this coating was very thin and imperfect, although in some instances the coatings were quite heavy. In certain cases the lines have been reconditioned and the kind of coating changed from time to time. Most pipe lines carry

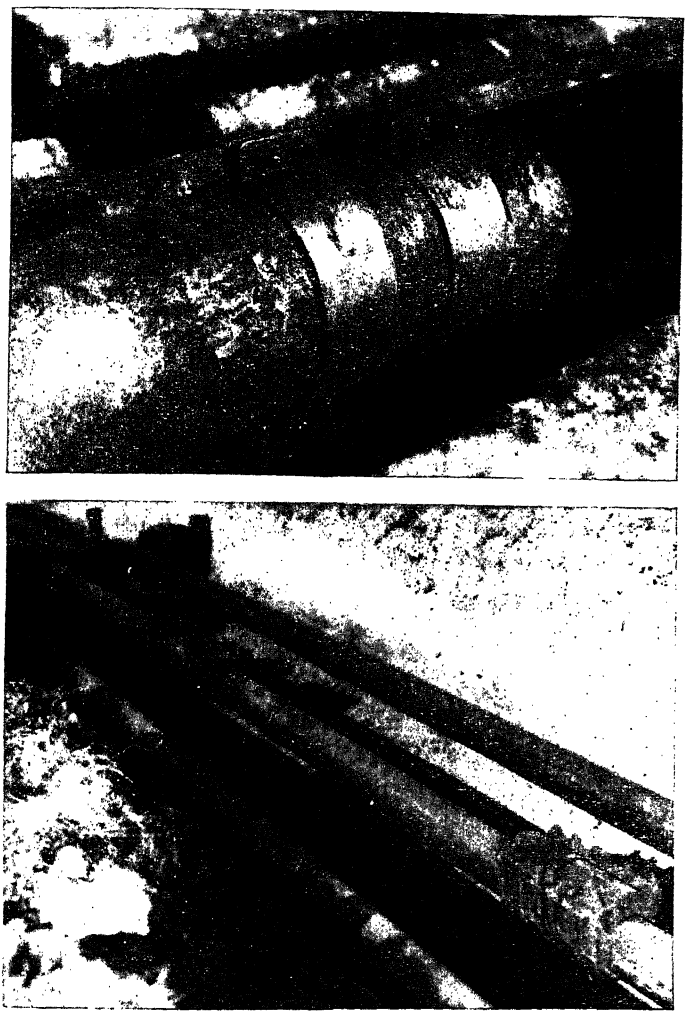

FIGURE 20.—*Two types of leak clamps.*
Top, home made, and bottom, commercial leak clamps.

currents which tend to protect certain portions of the line at the expense of other portions. Pipe networks in cities are frequently affected by stray currents from street railways, which modify the corrosive effects of the soils. The connection of one variety of pipe material to another, such as the connection of copper, brass, lead, or galvanized steel to cast iron, wrought iron, or steel mains, introduces additional galvanic cor-

rosion. The passage of a line through two different soils sets up a galvanic current. The pipe that lies in the same type of soil as the test specimens may be buried deeper or shallower, and thus lie in a soil horizon that is quite different in texture, aeration, acidity, or resistivity from that of the specimens. The interconnection of a new pipe with an old one sets up a condition that may accelerate the corrosion of the newer line. Two pipes of the same material in the same street or right-

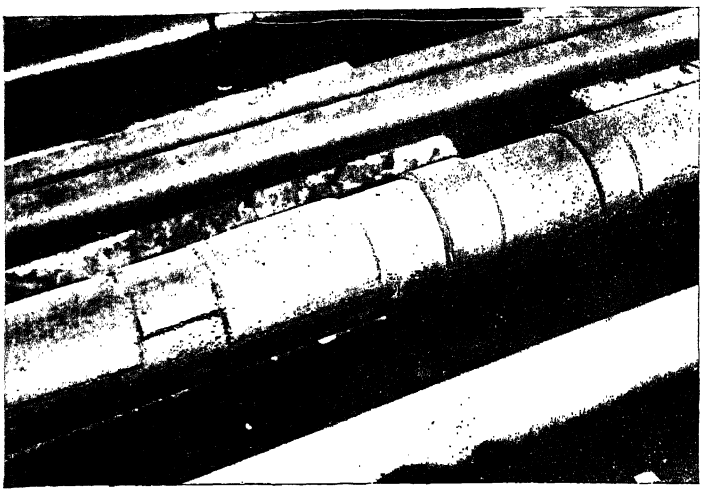

FIGURE 21.—*"Half-sole" (welded patch) method of pipe repair.*

of-way may corrode at different rates. In many cases records of the pipe lines are incomplete. In other cases the owners are reluctant to disclose their experiences because of possible effects on the valuation of their lines or the rates they may be allowed to charge for amortization as common carriers. For these reasons and others, no general comparison of the test data with the conditions of pipe lines has been attempted. However, a few comparisons will be made where conditions are especially favorable for such comparisons, although in no case are the conditions affecting the pipe line identical with those affecting the test specimens, and it is impossible to evaluate the effect of the differences accurately.

Soil 1. Allis silt loam.—Severe corrosion of service pipes in this soil has been reported, but definite data are not available. Ewing's equations indicate an average of one leak per 1,000 feet of 8-inch steel pipe in 25 years.

Soil 8. Fargo clay loam.—This soil is similar to much of that in the city of Winnipeg, where severe corrosion of cast-iron water mains has been reported. Originally, the corrosion was attributed to stray-current electrolysis, but the extent of the corrosion attributable to stray currents has not been established. Ewing's equations indicate that in this soil an 8-inch steel pipe should develop in 30 years an average maximum pit depth of 266 mils on a 1,000-foot length.

Soil 9. Genesee silt loam.—A 6-inch steel line paralleling the test site was renewed because of corrosion after 14 years. Ewing's equations indicate that this soil is not corrosive.

Soil 15. Houston black clay.—Severe corrosion of cast iron and steel has been reported in this soil. Table 51 indicates that this soil is not very corrosive.

Soil 23. Merced silt loam.—Leaks developed on an 8-inch steel line in this soil within 5 years. Table 51 shows this soil to be very corrosive.

Soil 27. Miller clay.—Frequent leaks developed on a 12-inch line in this soil in about 9 years. The data in table 28 are from observations on such a line in Miller clay somewhat better drained than that in which the specimens were buried. Ewing's equations indicate that an 8-inch steel pipe should average one leak per 1,000 feet in 27 years.

Soil 28. Montezuma clay adobe.—This is said to be a very corrosive soil, but no specific data have been obtained. Table 51 shows this to be one of the most corrosive soils tested.

Soil 29. Muck.—Water mains in the vicinity of the test site corrode rapidly. The corrosion was attributed to electrolysis at one time, but the actual cause of the corrosion has not been definitely determined. Table 51 shows this to be one of the most corrosive soils tested.

Soil 32. Ontario loam.—The test site lies within a few feet of a 38-inch steel water main having a ⅝-inch wall. Within 2,000 feet of the test site this line developed 25 leaks in 42 years. The line was protected by a japan varnish baked on. The length of the pipe in this soil at this location is 7,480 feet, in which length there were 50 leaks, or an average of one leak for 150 feet in 42 years. According to Scott's pit-depth–area equation, the National Bureau of Standards data indicate there should have been an average of one leak in 5,349 feet of pipe. The formula of Ewing would indicate that the length per leak should be greater. The Bureau's data show that in this case the soil is much less corrosive than experience proved it to be. However, this steel main is paralleled by a 36-inch wrought-iron main having a ⅜-inch wall which has developed no leaks in this soil in 61 years. The difference in the two experiences is greater than the difference between the test data and experience.

The difference in the performance of the two pipe lines may be explained in several ways. The materials used were different, as were the protective coatings. It has been shown [60], in certain cases at least, that when a new pipe is connected to an old one, the latter is protected at the expense of the former. As for the difference between the results calculated from the tests and the leak records of the two pipe lines, it is obviously impossible for the experimental results to agree with both experiences. Most of the leaks on the steel line occurred on the top three-fifths of the pipe. This is rather unusual, as most cases of severe corrosion occur on the bottom of the line. The severe corrosion of the steel line may be the result of a difference in soil conditions at the top and the bottom of the pipe or because the coating on the top of the pipe was injured by the backfill. The record of these pipe lines illustrates very well how conditions not duplicated in a test may alter the results when the material tested is used in a practical way.

Soil 35. Ramona loam.—The specimens at this site are laid adjacent to a 6-inch cast-iron gas main that has carried gas for 29 years without developing a leak in the city block containing the specimens. This block also contains five services, one of which served without a leak for more than 25 years. Another service developed a leak in 9 years. Using Scott's pit-depth–area relation, the average of the maximum pit depths for 500 feet of 6-inch cast iron is 468 mils for a period of 29 years. This indicates that the cast-iron pipe in this soil, the wall thickness of which is 430 mils, should have developed, on the average, one puncture per block at the time the information was obtained. However, the comparison of the field and experimental data is of doubtful value because the extent of

TABLE 52.—*Depth of the deepest pit on 4 feet of uncoated line pipe and on the adjacent 3-inch control pipe.*

[Depth in mils]

Section	Specimen	Sites[a] I. Temple, Tex.	II. Arkansas City, Kans.	III. Beaumont, Tex.	IV. League City, Tex.	V. Preble, Ind.	VI. Council Hill, Okla.	VII. Caney, Kans.	VIII. Spindle Top Gully, Tex.	IX. Long Beach, Calif.	X. Mt. Auburn, Ill.	XI. Skiatook, Okla.	XIII. Bunkie, La.	XIV. Chambersburg, Pa.	XVI. Cholame Flats, Calif.
1	Line	36	47	235	26	65	43	42	118	110	60	95	59	40	.....
	Control	49	45	H[b]	52	34	50	37	.....	106	52	130	40	58	.....
2	Line	24	57	280	73	55	70	69	62	100	46	159	52	38	.....
	Control	36	39	H	65	29	62	70	80+	94	48	55	28	46	.....
3	Line	30	60	216	60	65	42	46	105	78	45	105	85	45	.....
	Control	43	60	H	48	34	65	51	.....	135	49	44	32	51	.....
4	Line	36	68	229	51	41	61	47	158	47	62	109	126	38	.....
	Control	.....	.....	.....	70	74	30	50	.....	51	75	40	32	46	.....
5	Line	25	54	160	75	45	38	41	135	72	62	60	.....	31	.....
	Control	61	78	165	68	60	35	56	.....	45	69	48	.....	49	.....
6	Line	79	65	144	40	58	43	94	199+	100	66	75	150	35	.....
	Control	.....	.....	H	60	40	42	62	.....	105	.....	46	27	42	.....
7	Line	36	65	200	68	45	41	55	168	83	57	120+	122	26	.....
	Control	49	40	.....	50	40	37	51	.....	109	64	49	38	43	.....
8	Line	26	65	216	33	35	46	59	190	80	46	92+	109	37	.....
	Control	48	67	.....	50	42	.....	66	.....	60	57	72	39	59	.....
9	Line	35	77	183	54	36	57	116	87	83	56	102+	74	36	.....
	Control	60	37	.....	54	55	.....	95	.....	78	68	.....	42	49	.....
10	Line	30	58	126	70	41	53	177	121+	154	44	102+	62	46	.....
	Control	48	41	.....	120	37	.....	45	.....	89	51	.....	49	.....	.....
11	Line	54	68	200	34	45	51	61	156+	135	48	51+	76	41	.....
	Control	49	46	.....	90	53	52	50	.....	89	40	.....	53	.....	.....
12	Line	28	45	131	10	46	52	76	157+	175	.....	102+	105	.....	.....
	Control	.....	.....	152	70	59	53	63	.....	98	.....	47	41	.....	.....
13	Line	38	61	127	.....	50	.....	106	.....	60	75	52+	152	.....	.....
	Control	.....	65	123	.....	38	.....	61	.....	51	35	.....	60	.....	.....

[a] See Appendix 2 for description of soils at test sites.
[b] H indicates that the pipe wall was punctured. The wall thicknesses are as follows: 10-in. pipe, 365 mils; 8-in., 322 mils; 6-in., 280 mils; 3-in. control pipe, 203 mils.

the pipe in Ramona loam has not been determined, also as the pitting factor for cast iron is greater than for steel, the value for a should be less, and furthermore, cast iron may be punctured by corrosion and still carry low-pressure gas without leaking.

A little additional light on the relation between the corrosion of pipe lines and that of short lengths of pipe is furnished by the American Petroleum Institute's tests of protective coatings [61][5]. Bare sections of pipe line were left between two coated sections. Opposite each bare section a 30-inch length of 3-inch pipe was placed in each trench as a control specimen. Table 52 shows the deepest pit on sections of the line and adjacent control pipes. The line pipes differed in diameter.

Although the area of the pipe was from five to nine times that of the control, there is no definite relation between the pit depths on the two areas. Because some of the coatings on the line were rather porous, the pipe beneath them may have been anodic on account of differential aeration, and so may have protected the bare sections. The 13 sections were distributed along about 1,100 feet of pipe, and the difference in pit depths on different sections illustrates the dispersion of pit depths on pipe lines. However, table 28 is a much better presentation of this phenomenon, as it pertains to a pipe that was not coated.

Although a review of these comparisons of test data with actual performance indicates no very close relation between the two, usually the soils which the test has shown to be corrosive are shown by experience also to be corrosive. Corrosion is affected by so many factors that it can scarcely be expected that any test could completely duplicate the conditions which buried metals encounter in service. Knowledge of service conditions is in most cases so incomplete that it would be difficult to use an equation that would take account of all significant field conditions even if such an equation could be developed.

VII. RESULTS OF FIELD TESTS ON MISCELLANEOUS NONFERROUS MATERIALS

1. COPPER AND COPPER ALLOYS

The first copper-alloy specimens buried in 1924 in the National Bureau of Standards tests consisted of four high-copper cast brasses connected as caps to nipples of brass (Muntz metal), lead, and galvanized steel. The final results of these tests are reported in Research Paper RP945 [62]. The cast caps each weighed about 150 grams (5.3 ounces). The nipples were cut from ½-inch pipe, each having an exposed length of 2-inches, that is, about 5 square inches. Table 53 shows the approximate composition of the cast caps.

TABLE 53.—*Composition of cast brass caps.*

Mixture No.	Cu	Sn	Pb	Zn	Fe
1	85.5	3.5	4.8	6.2	.....
2	87.0	5.9	1.8	5.3	.....
3	91.8	0.1	0.3	7.7	.....
4	75.0	1.4	2.6	20.0	1.0

The small size of the specimens, their irregular shapes, and the galvanic potentials and small corrosion losses combined to make precise results impossible and a detailed report on the specimens from each site seems unnecessary. Figure 22 shows the average rates of loss for

[5] See section VIII, B for a description of the tests.

each material on all soils. Figure 23 permits a comparison of these losses with losses of similar materials unaffected by galvanic action. It was evident that the connecting of the different materials accelerated the corrosion of the nipples, and reduced the corrosion of the cast caps. The intensity of the galvanic corrosion was affected by the relative areas of

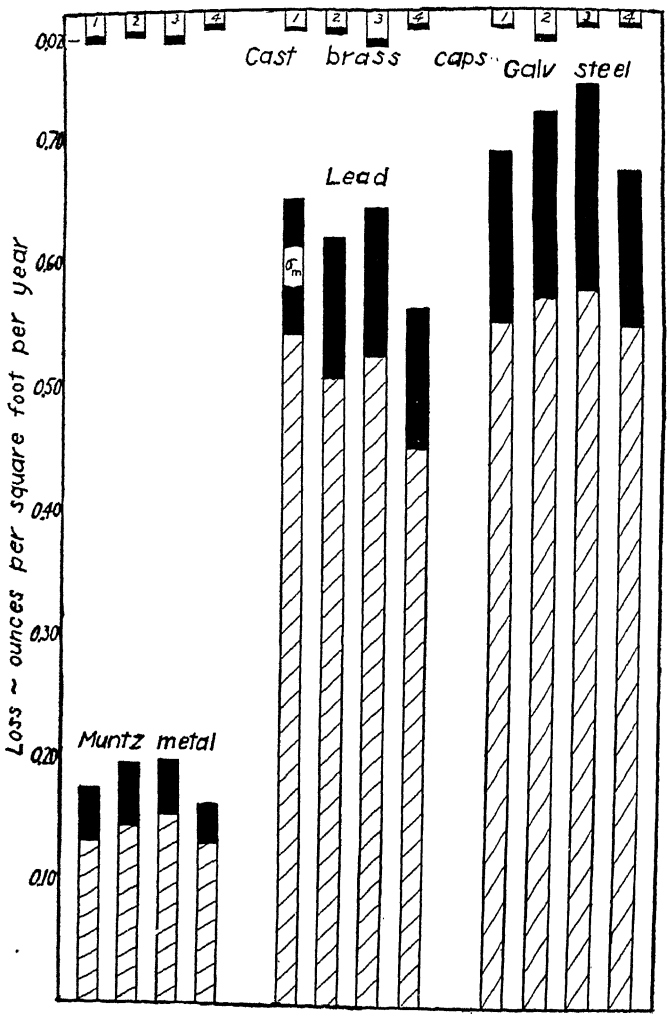

FIGURE 22.—*Average rates of corrosion of cast-brass fittings and attached nipples in 15 soils.*

the anodic and cathodic parts of the combination and no generalization could be drawn, except that connecting two metals in the presence of an electrolyte tends to cause one to corrode more rapidly and reduces the corrosion of the other.

In 1926 a few copper and copper-alloy pipes and rods were buried in 47 soils. The compositions of these materials are given in table 9. Table 54 shows the rates of corrosion of these materials based on exposures of approximately 8 and 13 years. As stated in the discussion of the ferrous

materials, rates of corrosion change with the duration of the exposure and should not be used to predict corrosion for any period except that used in deriving the rate. However, the data in table 54 are comparable with each other. They show that in most soils the losses of weight during 8 years were very small, and that the maximum penetration was slight.

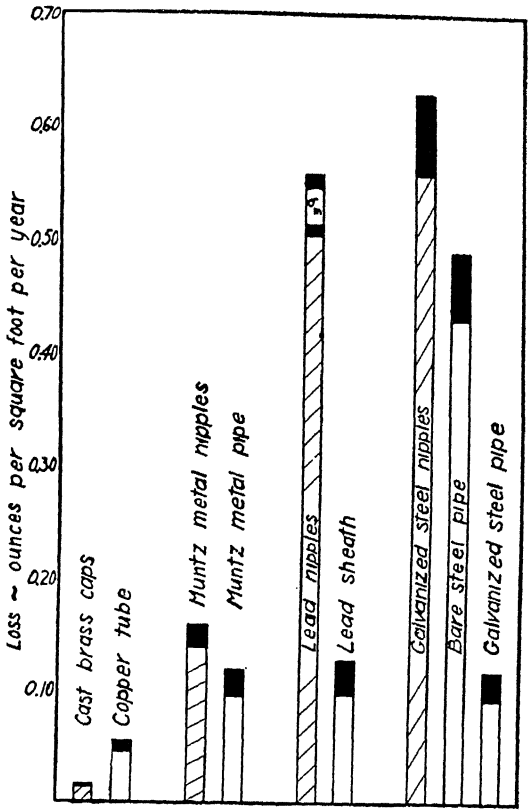

FIGURE 23.—*Effect of interconnecting different metals.*
The brass caps were connected to lead and galvanized iron. All the nipples were connected to brass caps.

The table puts the brass alloys in too favorable a light because it does not show the deterioration of these materials due to dezincification or selective corrosion. This is recognized as copper-colored spots or areas on the surface of the metal and by a loss of strength, but not of form, if the dezincification penetrates deeply. According to McKay and Worthington [63], accidental variations in the soil solution or in the alloy result in concentration or galvanic cells and at the anodic area the alloy goes into solution, copper is then redeposited from the solution at or near the points where the corrosion occurred. This deposition of copper sets up another galvanic cell and corrosion continues to spread and to penetrate the alloy. The acid around the anode keeps the zinc in solution and it migrates into the soil. According to these authors, the most favorable conditions for dezincification are a good conducting solution and a slightly acid condition, with the presence of oxygen. In the Bureau's tests the most serious dezincification occurred in cinders that had a pH of 8.0 and poor aeration. Serious dezincification also occurred in Docas

clay, a poorly-drained soil with a pH value of 8.3. Table 54 indicates that some dezincification of three high-zinc brasses occurred in all soils in the tests of corrosion-resistant materials. Figures 24 and 25 are photomicrographs of corroded areas of two types of brass showing the uncorroded metal and the dezincified (corroded) metal.

FIGURE 24.—*Yellow brass exposed 9.53 years to Sharkey clay.*
Transverse section showing uncorroded metal (below) and dezincified metal (above) × 500.

Tables 55 and 56 show the losses of weight and pit depths for a variety of copper alloys exposed for approximately 9 years to 13 soils that were corrosive with respect to ferrous materials. The corrosion of low-carbon steel in these soils is shown for comparison. The relative corrodibilities of the several alloys with respect to each other remain approximately the same except in a few soils.

The corrosion resistance of copper has been attributed [20] to its nobility, that is, low solution potential and to the density of the oxide film which forms on the surface. Sulfide and reducing conditions are corrosive to copper. It will be noted that the soils that are most corrosive to copper are mostly wet, organic soils. Such soils frequently contain bacteria which reduce sulfates to sulfides. According to Ewing [29], the corrosion of copper in such soils as Docas clay is probably caused by differential aeration, and is stimulated by the action of chlorides. The same author attributes the corrosion of copper in such soils as muck and peat to organic acids that tend to dissolve the protective oxide film. The most corrosive condition in the Bureau's test sites was in cinders (soil 67). As an analysis of a sample of these cinders from which the large clinkers had been removed showed 26 percent of carbon, it seems probable that much of the corrosion was the result of galvanic action between the carbon and the test specimens. Sometimes, cinders from completely burned coal are not corrosive. They may be inert and act much like sand. To permit a better comparison of the materials, table 57 has been prepared. It is based on the averages of data for four

periods of exposure in 11 of the soils of table 56. Data for soils 63 and 67 were omitted because of the destruction of some of the materials at these test sites.

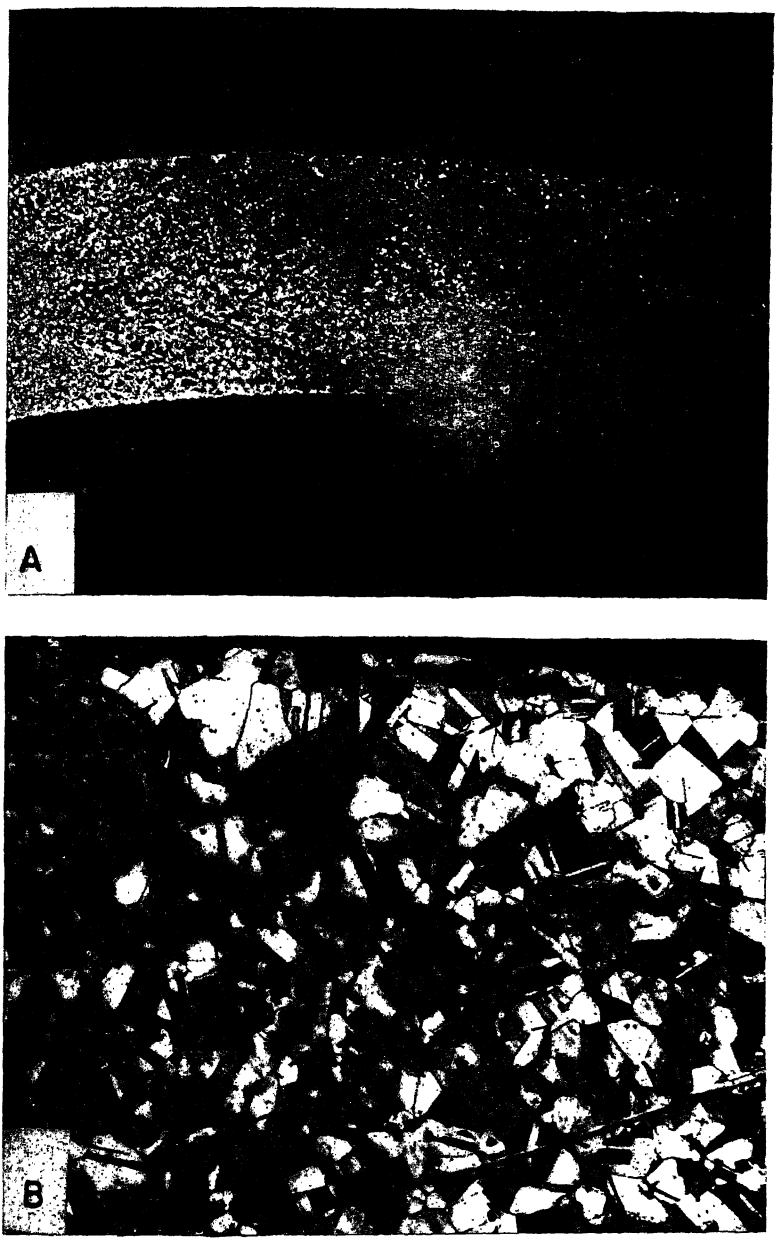

FIGURE 25.—*Two-and-one leaded brass (leaded silicon brass) exposed 9.53 years to Sharkey Clay*

A, transverse section showing transition from uncorroded metal at left to complete dezincification at right, × 15; *B*, section showing partial dezincification, the dezincification being more severe at the left, × 250.

TABLE 54.—*Corrosion of copper-rich alloys exposed for 8 years and for 13 years.*

[For the condition, the letters indicate the worse of 2 specimens. The figures are rates of maximum penetration, in mils per year.]

M, Shallow metal attack, roughening of the surface but no definite pitting.
P, Definite pitting, no pits greater than 6 mils.
U, Unaffected by corrosion.
S, severe uniform corrosion, impossible to measure penetration because of even destruction of surface.
D, selective corrosion such as dezincification over large areas.
d, selective corrosion in spots.
Z, destroyed by dezincification.

Soil No.	Duration of test	Average rate of loss of weight (oz/ft²)/yr						Condition of surface and pit depth				
		Copper pipe		Brass		Cu-Zn-Ni rod,	Cu-Al rod,	Copper pipe		Brass pipe,	Cu-Zn-Ni rod,	Cu-Al rod,
		M	P	Pipe, B	Ell. Me	A	N	M	P	B	A	N
	Years											
1	8.07	0.060	0.063	0.097	0.185	0.157	0.057	1.5	P	M, D	P, d	M, D
2	13.54	.023	.016	.065	.090	.101	.019	P	P	P, D	P, D	M
3	8.01	.027	.029	.074	.109	.156	.063	P	P	1.2, d	1.2, d	D
4	7.94	.019	.019	.144	.....	.176	.070	1.3	M	P, D	1.3, d	D
5	13.36	.030	.032	.059	.317	.118	.045	0.6	P	P, D	0.5, D	P
6	13.33	.011	.0093	.017	.025	.056	.0023	P	P	P, d	P, D	P
7	13.44	.036	.026	.188	.....	.155	.032	P	P	S, D	0.07	P
8	7.96	.024	.019	.018	.319	.136	.026	1.5	1.3	M, d	1.5, d	1.9, d
9	13.44	.030	.036	.174	.092	.165	.011	P	P	0.5, D	0.9, D	P
10	13.18	.076	.095	.235	.....	.207	.037	0.8	0.5	0.6, D	0.8, D	P
12	7.96	.312	.278	.222	.....	.199	.090	1.5	S	P, D	M, d	P, d
13	7.96	.023	.031	.101	.024	.012	.028	P	P	M, D	M, d	M, d
14	7.97	.040	.025	.044	.089	.096	.017	P	.9	P, d	1.9, d	M, d
15	7.97	.013	.016	.030	.....	.045	.026	M	M	D	d	d
16	7.96	.057	.058	.170	.166	.234	.093	3.3	1.9	1.3, D	0.9, d	d
17	7.96	.037	.040	.059	.257	.108	.049	M	M	M, d	P, d	D
18	7.97	.0076	.0077	.021	.070	.044	.013	U	M	M, d	1.3, d	U
19	7.97	.039	.040	.122	.067	.165	.027	1.1	P	P, D	1.3, d	M, d
20	8.08	.042	.039	.044	.193	.138	.044	1.5	1.2	P, d	P, d	D
22	7.98	.068	.070	.195	.283	.277	.075	1.9	1.0	1.1, D	P, d	M, D
23	7.96	.118	.135	.752	1.85	.288	.169	1.9	1.3	Z	U	D
24	13.18	.019	.018	.025	.....	.030	.018	P	P	P, d	P, D	P
25	7.96	.012	.011	.051	0.142	.126	.043	P	U	P, D	P, d	D
26	13.44	.013	.012	.072	.058	.118	.034	P	P	P, D	P, D	P
27	13.58	.012	.012	.046	.080	.063	.023	P	P	P, D	P, D	P

28	7.96	.084	.079	.080	.....	.163	.107	P	P	M, D	P, d	M, D
29	7.97	.123	.116	.275	.....	.257	.082	P	P	P, D	1.9, d	M, d
30	13.39	.0078	.0097	.014	.048	.032	.0071	P	P	P, D	P, D	P
31	13.66	.0083	.0086	.019	026	.022	.026	P	P	P, d	P, D	M
32	7.93	.049	.018	.089	.152	.129	.016	U	M	1.0, D	1.3, d	d
33	7.96	.137	.117	.175	.218	.208	.040	0.9	1.0	P, D	1.3, d	M, d
34	7.97	.016	.022	.057	.080	.177	.021	M	P	M, D	P, d	d
35	7.95	.017	.016	.020	.422	.063	.039	M	P	D	1.0, d	D
36	13.61	.019	.019	.049	.039	.087	.014	P	P	0.7, D	0.7, D	P
37	7.97	.169	.162	.152	.274	.175	.060	1.8	1.3	P, D	P, d	M, d
38	7.97	.025	.043	.028	.037	.034	.019	M	P	M, d	P, d	U
40	7.98	.125	.168	.349	.330	.385	.092	2.3	4.1	1.8, D	1.9, d	d
41	13.38	.027	.030	.083	.....	.126	.035	P	P	P, D	0.5, D	P
42	7.97	.047	.049	.095	.089	.154	.057	P	1.1	P, D	1.9, d	P, D
43	7.95	.635	.555	.026	.022	.007	.022	S	S	M, d	U	2.3
44	7.97	.079	.061	175	.....	.248	.026	P	P	1.3, D	2.4, d	P, d
45	7.95	.033	.030	016	.214	.081	.030	1.0	1.0	d	1.0, d	D
47	13.36	.032	.035	.037	.30	.101	.056	1.2	0.8	P, D	P, D	P

TABLE 55.—*Loss of weight of copper and copper alloys exposed for 9 years.*

[In ounces per square foot]

Soil		Exposure	Tough pitch copper	Deoxidized copper	Red brass	Admiralty metal	2-and-1-leaded brass	Brass 66% Cu 33% Zn	Muntz metal	Bronze 97% Cu 1% Si 1.8% Sn	Alloy				Low carbon steel
											98% Cu 1.5% Si 0.2% Mn	98% Cu 1.5% Si 0.2% Mn	95% Cu 3% Si 1% Mn	75% Cu 20% Ni 5% Zn	
No.	Type		C	A	F	H	K	J	L	E	N	[a] N_1	D	G	N
		Years													
53	Cecil clay loam	9.47	0.24	0.22	0.25	0.29	0.47	0.41	0.52	0.37	0.30	.....	0.36	0.27	4.09
55	Hagerstown loam	9.11	.20	.18	.25	.25	.36	.30	.77	.35	.30	.....	.28	.20	3.82
56	Lake Charles clay	9.42	.71	.78	.70	.57	.89	.94	1.21	.76	.62	.....	.63	.78	28.76
58	Muck	9.51	1.95	2.10	2.06	2.09	[b] 1.66	3.33	5.25	2.11	1.97	.....	2.12	1.40	16.24
59	Carlisle muck	9.12	0.12	0.11	0.12	[c] 0.086	0.20	0.029	0.031	0.17	[d] 0.24	.....	0.15	0.088	4.70
60	Rifle peat	9.24	7.26	5.01	3.55	[d] 2.85	[b] 3.22	[d] 4.21	[d] 4.56	[d] 3.22	[d] 3.96	1.82	4.46	3.61	16.72
61	Sharkey clay	9.53	0.33	0.35	0.41	0.51	0.87	[i] 1.22	[i] 2.58	0.61	0.48	.....	0.52	0.43	5.78
62	Susquehanna clay	9.47	.36	.48	.43	.53	.71	0.94	1.79	.69	.57	.....	.60	.47	6.65
63	Tidal marsh	9.55	4.46	[i] 4.22	[i] .75	.18	[d] .52	.076	0.10	[d] 4.38	6.96	.....	5.32	3.56	9.03
64	Docas clay	9.21	2.80	5.32	[d] 1.12	.98	[d] 1.07	[i] 1.94	11.53	2.30	4.87	.....	2.88	[d] 0.74	[e] D
65	Chino silt loam	9.25	0.26	[i] 0.24	0.28	.58	1.39	[i] 1.60	[i] 1.45	[i] 0.96	[i] 0.62	.....	[i] 0.48	.44	12.86
66	Mohave fine gravelly loam	9.23	.45	[d i] .62	.77	.80	[i] 0.95	[d] 1.16	[i] 1.41	[d] 1.53	[d] .51	0.34	.55	[d] .60	18.56
67	Cinders	9.24	9.84	11.50	8.46	8.27	([f]Z)	[gi] 23.10	([f]Z)	8.76	22.51	23.17	13.47	6.28	[h] 58.39

[a] These specimens had brazed joints; data for 1 specimen only.
[b] Data for 1 specimen only.
[c] Average for 3 specimens.
[d] Data for the individual specimen differ from each other by more than 50%.
[e] D indicates specimens destroyed by corrosion.
[f] Z indicates specimens destroyed by dezincification.
[g] Data for 1 specimen; the other specimen was destroyed by dezincification.
[h] Data for 1 specimen; the other specimen was destroyed by corrosion.
[i] Average loss of weight for 1939 removals is greater.

TABLE 56.—*Maximum penetration of copper and copper alloys exposed for 9 years.*

[In mils]

M, shallow metal attack, roughening of the surface but no definite pitting.
P, definite pitting, no pits greater than 6 mils.
s, uniform corrosion, impossible to measure true penetration.
D, selective corrosion, such as dezincification over large areas.
d, selective corrosion over small areas.
Z, specimens destroyed by corrosion (dezincification).
+, one or both specimens punctured.

Soil No.	Tough-pitch copper	Deoxidized copper	Copper with soldered joints	Red brass	Admiralty brass	Two-and-one leaded brass	Brass 66% Cu 33% Zn	Muntz metal	Bronze 97% Cu 1% Si 1.8% Sn	Alloy 98% Cu 1.5% Si 0.2% Mn	Alloy 98% Cu 1.5% Si 0.2% Mn	Alloy 95% Cu 3% Si 1% Mn	Alloy 75% Cu 20% Ni 5% Zn	Low-carbon steel
	C	A	[a] M	F	H	K	J	L	E	N	[b] N	D	G	N
53....	6	P	13	10, D	20, D	P, D	6, D	6, D	12	P	.....	8	8, D	59
55....	8	P	8	7, D	20, D	7, D	10, D	6, D	[c] 20	P	.....	8	6, D	59
56....	P	P	[d] 15	P, D	P, D	P, D	P, D	P, D	12	P	.....	M	P, D	[e] 154+(7)
58....	10	[c] 14	18	10, D	[f] 26, D	[g] P, D	8, D	6, D	53	12, s	.....	12, s	P, D	110, s
59....	6	P	9	M	[d] P	P	M, D	P, D	20	M	.....	P	P	[c] 40
60....	40, s	38, s	[c] 17, s	34, D	[c] 16, s, d	[c] 12, D	[c] 33, D	[c] 27, s, D	18, s	10, s	8	21, s	32, D	[c] 27, s
61....	8	8	10	[f] 7, D	[c] 35, D	6, D	6, D	[f] 12, D	[c] 37	10	.....	P	[f] P, D	[c] 96
62....	8	8	10	14, D	[f] 24, D	P, D	13, D	P, D	22	P	.....	6	12, D	[c] 87
63....	6	10, s	6, s	6	P, d	P	M, D	P, d	10, s	12, s	.....	9	P	54
64....	[c] 14	[c] 16	[c] 13	26, d	[c] 46, D	[c] 15, D	[f] 20, D	[c h] 42+, D	34	21, s	.....	[c] 16	[c] 18, D	154+(5, 7)
65....	[f] 10	P	[f] 8	P, D	[f] 13, D	P, D	[c f] 18, D	P, D	[f] 22	20	.....	11	P, D	112
66....	P	10	[f] 13	P, D	[f] P, D	P, D	8, D	P, D	22	13	P	9	P, D	154(5, 7)
67....	51, s	58, s	145+(5)	[c] 54, D	68, s, D	Z(5, 7)	[i] 132+(2, 5, 7)	Z(2, 5, 7)	102	145+	90, s	80, s	36, D	154+(2, 5, 7)

[a] These specimens had streamlined caps and couplings soldered in place.
[b] These specimens had brazed joints; data for only 1 specimen.
[c] Maximum pits for individual specimens differed from each other by more than 50 percent.
[d] Data for 3 specimens.
[e] A number in parentheses after the pit depth indicates that 1 or both specimens of a previous removal was punctured, e. g., (5) indicates that the specimen was punctured after 5 years.
Average pit depths of 1939 removals are greater.
[g] Data for 1 specimen only.
[h] Hole in 1 specimen due to dezincification. The mate, although it had no measurable pits greater than 8 mils, was badly dezincified, as indicated by the flat sound when the pipe was struck with another piece of metal.
[i] 1 specimen destroyed by dezincification.

TABLE 57.—*Relative loss of weight of copper and copper alloys.*

[Average of four periods of exposure, 11 soils]

Material		Composition			Average	Standard deviation	Standard error
Symbol	Type	Cu	Zn	Pb			
		%	%	%	%	%	%
C	Tough-pitch copper	99.9	.....	.....	100	.....	.....
A	Deoxidized copper	99.94	.....	.....	144	93	13
F	Red brass	85.2	14.8	.....	105	32	5
H	Admiralty metal	71.3	27.4	.....	121	53	8
K	Two-and-one leaded brass	67.1	31.1	0.8	176	176	25
J	Brass	66.5	33.1	.4	225	229	33
L	Muntz metal	60.1	39.6	.4	492	942	136
			Si	Sn			
E	Bronze	97.2	1.0	1.8	193	144	21
N	Copper-silicon alloy	98.1	1.0	.....	154	79	11
D	....do	95.5	3.2	.....	142	63	9
			Zn	Ni			
G	Copper-nickel alloy	74.5	5.0	20.0	104	54	8

The high standard errors for some materials indicate that their performance relative to copper was different at different test sites or for different periods of exposure. The table should be used with care, as the performance of a material under some specific conditions may be quite different from the average of its performance under a number of conditions. For example, Muntz metal corroded very little in tidal marshes, soils 43 and 63, but was quite unsuitable for most other corrosive soils.

The copper alloy containing approximately 60 percent of copper and 40 percent of zinc, commonly known as Muntz metal, is subject to dezincification under several soil conditions. To determine whether or not the addition of arsenic to this alloy would prevent dezincification, specimens of Muntz metal plates containing 0.08 percent of arsenic were added to the tests in 1939. Unfortunately, similar plates of ordinary Muntz metal were not buried at the same time. This makes it necessary to compare the behavior of the new materials with that of a section of pipe buried 7 years previously. Obviously, under these conditions small difference in performance may be accidental. Table 58 shows the loss of weight and the condition of the two materials exposed for approximately the same periods. It appears that the addition of 0.08 percent of arsenic was insufficient to prevent dezincification of the brass.

The effect of time on the rate of corrosion of nonferrous metals has not been examined as thoroughly as was done for ferrous materials. The loss of weight and pit depths in most soils are small, and this makes their accurate determination more difficult. In addition, the copper and copper-alloy specimens in the Bureau tests were exposed for shorter periods than the ferrous materials and the number of examinations has been less. In figure 26 are shown the losses of weight per unit area for several materials in three soils. The letter identifies the material (see table 57) and the number relates to the soil (table 55). The curves were drawn arbitrarily and might have been drawn differently, possibly with different significance. As drawn, curves J58, C58, and K58 indicate that the materials did not begin to corrode for a considerable time after burial, possibly because of a temporarily protective oxide film.

TABLE 58.—*Loss of weight and maximum penetration of Muntz metal exposed*

M, shallow metal attack, roughening of the surface but no definite pitting.
P, definite pitting but no pits greater than 6 mils.
s, uniform corrosion, no reference surface.
D, selective corrosion by dezincification over large areas (several square inches per square foot).
d, selective corrosion over small areas.
Z, specimens destroyed by dezincification.

Soil		Arsenical Muntz metal (sheet) B_1			Muntz metal (pipe) L		
No.	Type	Exposure	Loss of weight	Maximum penetration	Exposure	Loss of weight	Maximum penetration
		Years	*oz/ft²*	*Mils*	*Years*	*oz/ft²*	*Mils*
53	Cecil clay loam	1.91	0.18	P,D	1.96	0.19	P,d
55	Hagerstown loam	2.03	.16	P,d	1.89	.19	6,d
56	Lake Charles clay	1.91	.55	12,D	1.99	.14	M,d
58	Muck	1.91	.54	P,D	1.99	.20	P,d
60	Rifle peat	1.91	1.87	13,D	1.92	1.73	9,d
61	Sharkey clay	1.92	0.40	P,D	0.95	0.16	P,d
62	Susquehanna clay	1.90	.32	P,D	1.93	.33	P,d
63	Tidal marsh	1.88	[a].036	[a]P	2.04	1.41	M
64	Docas clay	1.90	.47	P	1.91	4.02	P,D
65	Chino silt loam	1.91	.21	P,D	1.91	2.43	M,D
66	Mohave fine gravelly loam	1.86	.30	8,d	1.92	[b].63	[b]P,d
67	Cinders	1.90	15.25	122,s,D	2.02	Z	Z
69	Houghton muck	1.90	0.30	P,D	.....	.....	.....
70	Merced silt loam	1.90	.28	12,D	.....	.....	.....

[a] Data for 3 specimens.
[b] Data for 1 specimen.

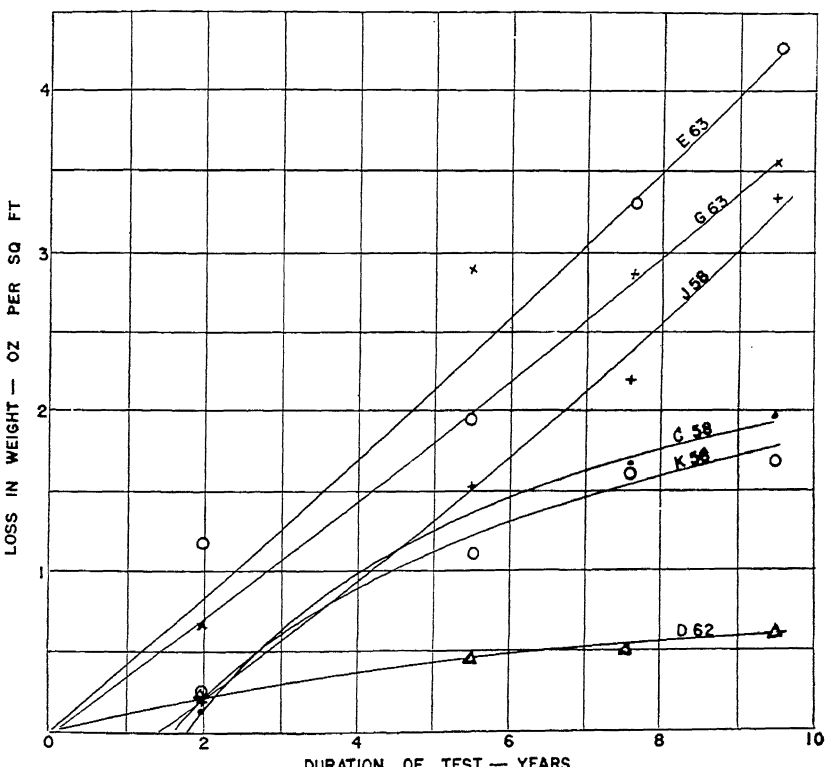

FIGURE 26.—*Loss-of-weight–time curves for copper and copper-alloy specimens.*
See tables 55 and 57 for identification of soils and specimens.

As in the case of the ferrous materials, the pit-depth data for the copper alloys are quite erratic and, because of the smaller depths and fewer removals, it is quite impossible to plot satisfactory pit-depth–time curves from most of the data. Some of the most nearly consistent data are shown in figure 27. The curves indicate that there is only a slight

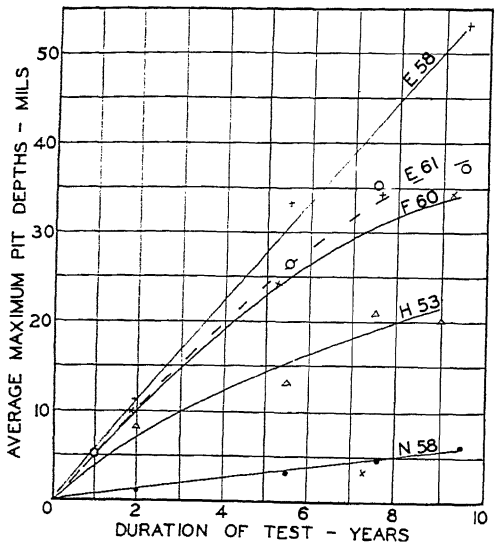

FIGURE 27.—*Pit-depth–time curves for several copper-alloy specimens.*
See tables 55 and 57 for identification of soils and specimens.

tendency if any for the rate of corrosion to decrease with time. This is probably because of the solubility of the corrosion products.

Somewhat more definite conclusions can be drawn after the specimens now in the ground have been removed, but it is improbable that the exact rates of corrosion of the copper-alloys can be determined from the tests. It is evident that, with a few exceptions with respect to soil types and alloys such as Muntz metal, the deterioration of copper alloys exposed to soil is much slower than that of any of the ferrous alloys except those high in silicon, chromium, or nickel. If more specific information is desidered, new tests in which soil and other conditions are controlled much more closely and which include a much greater number of specimens of the same material in each test site must be undertaken.

2. LEAD

Lead is used extensively underground in the form of water service pipes and cable sheaths. Most cable sheaths are placed in fiber, cement, or vitrified-clay ducts and are in contact with soil only as it is washed in from manholes. Occasionally, lead cable sheaths are laid directly in the ground. Parkway and similar power-distribution cable is laid directly in the earth, but in such cable the lead is surrounded by wrappings of steel tape and jute or other fiber impregnated with a bituminous material.

Table 59 shows the loss of weight and maximum depth of penetration of antimonial lead and commercial lead cable sheaths exposed for from 10 to 17 years. For comparison, similar data are given for a 12-inch

length of 3-inch Bessemer steel pipe (113 square inches) in the same soils. The area of the antimonial lead sheath was in most cases 370 square inches, whereas that of the commercial lead was 150 square inches. The duration of exposure of the lead and steel specimens in table 59 was somewhat different in some soils.

TABLE 59.—*Loss of weight and maximum penetration of lead cable sheath exposed 10 to 17 years.*

Soil		Duration of exposure	Antimonial lead A		Commercial lead H		Bessemer steel M	
No.	Type		Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration
		Years	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
1	Allis silt loam	11.65	4.02	120+	2.01	112+	11.56	101
2	Bell clay	[a]15.48	1.56	45	1.20	30	7.12	58
3	Cecil clay loam	[a]10.02	0.63	8	0.59	18	4.34	72
4	Chester loam	12.00	1.79	64	2.13	51	6.92	84
5	Dublin clay adobe	[a]15.56	3.51	120+	6.66	112+	8.58	62
6	Everett gravelly sandy loam	[a]15.53	0.37	22	0.26	28	1.88	20
7	Maddox silt loam	16.94	1.47	39	1.60	32	5.06	48
8	Fargo clay loam	11.76	0.73	12	.....	.....	8.29	111
10	Gloucester sandy loam	11.95	.89	26	1.05	15	4.94	54
11	Hagerstown loam	11.92	.48	36	0.38	15	1.74	81
12	Hanford fine sandy loam	[a]15.59	1.88	30	1.85	43	5.32	86
14	Hempsted silt loam	11.76	2.13	68	0.57	24	4.58	95
15	Houston black clay	[a]10.06	0.52	16	.36	25	8.11	72
17	Keyport loam	11.78	.43	36	.33	20	9.65	48
18	Knox silt loam	11.71	.50	20	.18	10	2.40	44
19	Lindley silt loam	11.63	1.31	36	.46	15	3.32	60
20	Mahoning silt loam	11.65	3.54	78	3.12	51	5.99	56
22	Memphis silt loam	11.65	1.72	32	1.00	19	7.78	65
24	Merrimac gravelly sandy loam	11.95	0.25	18	0.18	19	1.40	30
25	Miami clay loam	11.67	.53	44	.33	28	3.31	57
26	Miami silt loam	11.52	.47	22	.21	29	3.77	38
27	Miller clay	[a]15.69	1.37	39	.67	31	8.86	84
28	Montezuma clay adobe	9.60	2.12	52	.66	10	15.54	152
29	Muck	[a]10.08	3.55	14	3.45	34	14.84	119
30	Muscatine silt loam	17.04	2.28	56	1.04	51	6.91	76
31	Norfolk fine sand	[a]15.73	0.37	<6	0.28	15	4.08	66
32	Ontario loam	11.66	.59	12	.33	18	4.15	62
34	Penn silt loam	12.00	3.12	120+	.81	112+	5.31	50
35	Romona loam	[a]15.59	0.19	12	.31	37	3.21	36
36	Ruston sandy loam	[a]15.69	.69	17	.48	22	2.58	49
38	Sassafras gravelly sandy loam	12.01	.38	14	.30	25	2.23	43
39	Sassafras silt loam	12.00	1.77	47	1.18	36	6.36	94
41	Summit silt loam	17.41	0.77	41	0.50	27	7.03	101
43	Tidal marsh	12.02	.51	28	.23	13	13.15	75
44	Wabash silt loam	11.61	.82	22	.44	13	3.39	83
45	Unidentified alkali soil	11.73	.45	19	.24	23	9.29	98
46	Unidentified sandy loam	12.00	.98	42	.18	14	4.81	114
47	Unidentified silt loam	17.43	1.12	32	.79	30	5.37	48

[a] Duration of exposure for the Bessemer steel pipes was approximately 2 years longer.

Figures 28 and 29 show the progress of the loss in weight for a few soils. The letters near the curves indicate the kind of lead tested, and the numbers are the numbers of the test sites. The two identifications permit the reader to determine from tables 10 and 20 the known conditions of the test. Four of the curves indicate that the rate of corrosion of the lead specimens increased as the specimens became older; two other curves show decreasing rates of corrosion. All of the soils involved are nearly neutral in reaction. The curves do not indicate the distribution of the corrosion. Some idea of this can be gained from table 59. The pitting was greatest in soil No. 1 and least in soil No. 8, which contained some sulfates. After examining the Bureau's data on com-

mercial lead specimens exposed from 10 to 17 years, Ewing [29] divided the types of corrosion as follows: No corrosion, concentrated attack, and uniform attack. The soil characteristics he associated with the first class were high pH and high sulfates. The second type of corrosion occurred

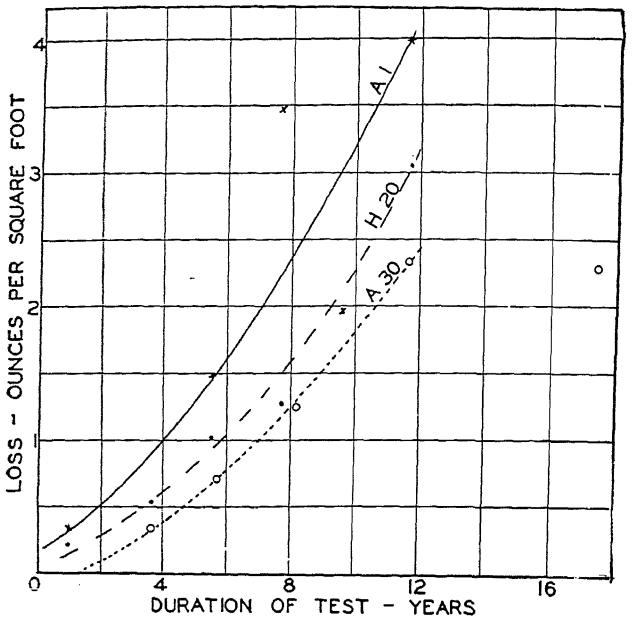

FIGURE 28.—*Loss-of-weight–time curves for lead sheath in different soils.*

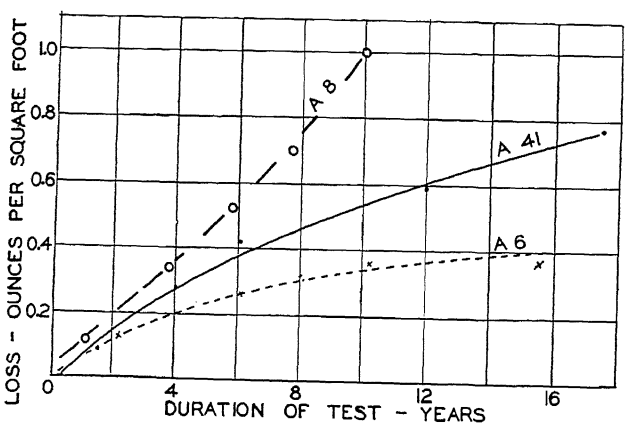

FIGURE 29.—*Loss-of-weight–time curves for lead sheath in different soils.*

in neutral soils, where apparently the original protective film broke down in spots. The third class of corrosion occurred in reducing soils, which apparently destroyed the protective film. Ewing recognized that other factors affected the corrosion of many specimens, but the data are insufficient to identify these factors.

In 1937 three varieties of lead-alloy pipe, such as are used for water service, were buried in 14 soils. Table 60 shows the extent of the cor-

rosion of these materials after exposures of approximately 4 years. No material is either worst or best in all soils. On the average, the antimonial lead is least subject to pitting. However, in the earlier tests, antimonial lead that contained much less antimony than the later antimonial-lead specimens was inferior to commercial lead. The differences in losses or pit depths are small, and may be due to chance. More specimens remain to be removed at later dates. A point shown quite positively is that in many soils the pitting of lead is sufficiently deep within a few years to puncture lead coatings of the usual thickness. The potential between lead and iron accelerates the corrosion of iron when the two metals are in contact in the presence of moisture. The data indicate, therefore, that in many soils only a very thick coating of lead would protect iron, and even such a coating would be unsatisfactory in a few soils where the rate of penetration for lead is as great as it is for iron.

TABLE 60.—*Loss of weight and maximum penetration of lead pipe exposed 4 years.*

Soil		Chemical lead[a]		Tellurium lead[b]		Antimonial lead[c]	
No.	Type	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration
		oz/ft²	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
53	Cecil clay loam	0.21	12	0.31	20	0.22	10
55	Hagerstown loam	.20	26	.28	26	.15	18
56	Lake Charles clay	.45	37	.82	48	.50	52
58	Muck	2.41	28	2.80	56	2.12	58
60	Rifle peat	0.28	15	0.20	10	0.22	[d]P
61	Sharkey clay	2.21	39	1.75	30	1.75	42
62	Susquehanna clay	0.93	29	0.64	31	1.03	30
63	Tidal marsh	.015	18	[e].015	[e]12	0.013	16
64	Docas clay	.19	16	.18	11	.19	12
65	Chino silt loam	.13	24	.16	16	.21	15
66	Mohave fine gravelly loam	.10	34	.12	41	.12	15
67	Cinders	12.21	104	13.22	94	4.21	90
69	Houghton muck	0.81	15	1.08	12	1.04	7
70	Merced silt loam	.12	14	0.15	27	0.14	12

[a] Cu, 0.056%; Bi, 0.002%; Sb, 0.0011%.
[b] Cu, 0.082%; Te, 0.043%; Sb, 0.0011%.
[c] Cu, 0.036%; Bi, 0.016%; Sb, 5.31%.
[d] P, definite pitting but no pits greater than 6 mils.
[e] Data for 1 specimen only.

3. ZINC AND ALUMINUM

Zinc is not used extensively for underground pipes or containers but is frequently used as a coating and in recent years it has been used in considerable quantities as anodes for cathodic protection. For the latter use it is essential that it continue to corrode as it is the current associated with the corrosion of the zinc that protects the metal to which zinc is connected.

Table 61 indicates the extent of the corrosion of two varieties of zinc plates exposed for approximately 4 years. Comparison of this table with the data on 2-year exposures [64] shows that in most soils the corrosion was nearly proportional to the duration of the exposure. However, in four soils high in salts the rate of corrosion was much less for the longer exposures. Comparison of the rates of corrosion of zinc and steel shows that steel loses weight from two to four times as fast as zinc in most soils during the first 4 years of exposure. The maximum penetration of

steel is correspondingly greater for 4-year-old specimens. However, as the rate of corrosion decreases more rapidly for steel than for zinc, the ultimate rates for the two materials may be nearly the same for long periods of exposure. In some of the highly organic soils, zinc loses weight

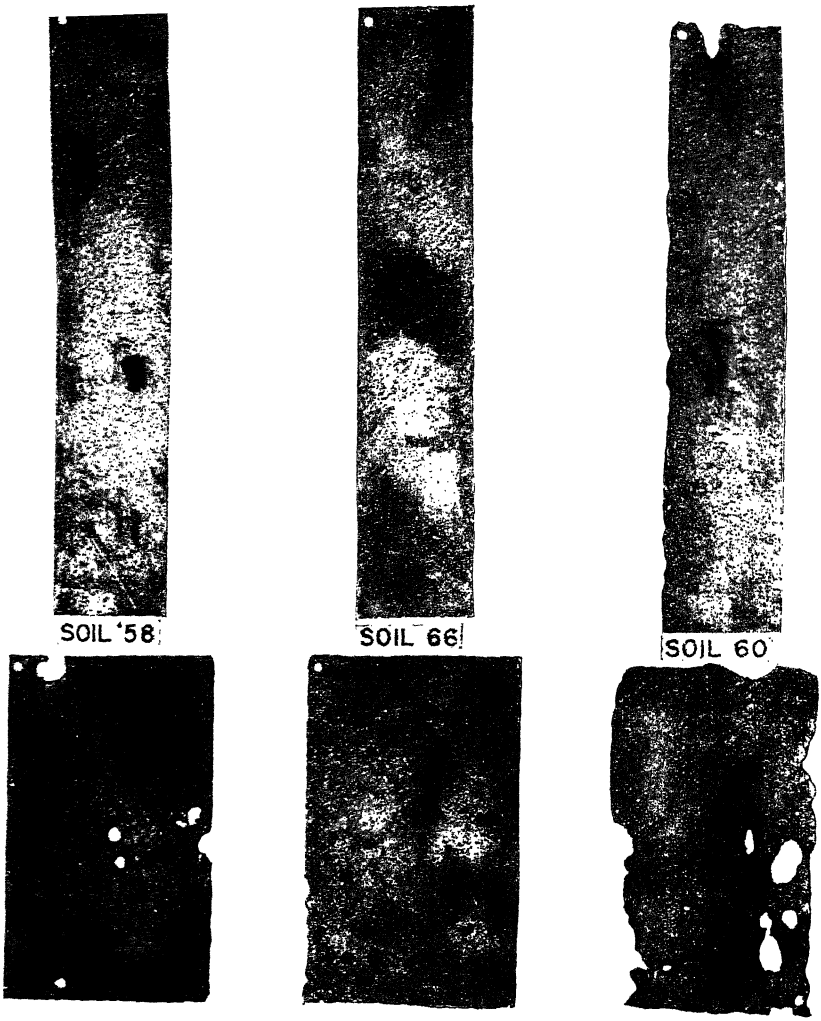

FIGURE 30.—*Rolled (above) and die-cast (below) zinc buried in muck (soil 58), in Mohave fine gravelly loam (soil 66), and in Rifle peat (soil 60), approximately 4 years each.*

faster than steel, and the penetrations of the two metals are of the same order. Figure 30 shows specimens of rolled and die-cast zinc exposed to three soils.

Figure 31 shows the relation of the average maximum penetration to the duration of exposure of zinc specimens to five soils. Each point is based on the average of the deepest pits on each of two specimens. In two of these soils the rates of penetration appear to increase with the period of exposure.

TABLE 61.—*Loss of weight and maximum penetration of zinc plates exposed for 4 years.*

Soil		Rolled zinc, Z		Die-cast zinc, CZ	
No.	Type	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration
		oz/ft²	*Mils*	*oz/ft²*	*Mils*
53	Cecil clay loam	0.62	10	0.54	22
55	Hagerstown loam	.60	[a] 8	.61	[a]20
56	Lake Charles clay	3.42	[b]26	4.96	30
58	Muck	5.09	66	6.33	[c]125+(2)
60	Rifle peat	10.36	[a]100	14.98	125+
61	Sharkey clay	0.96	8	1.12	28
62	Susquehanna clay	1.24	9	0.60	16
63	Tidal marsh	[b]2.30	34	1.43	24
64	Docas clay	0.57	18	2.53	20
65	Chino silt loam	.76	36	0.76	16
66	Mohave fine gravelly loam	[b]2.61	[b]28	4.74	124+
67	Cinders	[d]12.16	[a]118+(2)	13.08	125+
69	Houghton muck	1.70	10	1.64	36
70	Merced silt loam	[d]1.62	[b]102+	[d]2.19	[b]80+

[a] Uniform corrosion; no reference surface left.
[b] Data for individual specimens differed from the average by more than 50 percent.
[c] +Indicates that 1 or both specimens punctured by corrosion from 1 side of the plate. (2) indicates that 1 specimen from the previous removal was punctured after 2 years.
[d] Data for 1 specimen only; the other specimen was destroyed by corrosion.

The National Bureau of Standards obtained a few data on aluminum and two of its alloys exposed to only five soils. The test specimens measured 2 by 6 inches. In some of the soils, the duralumin was completely converted to a greenish-white paste. Intergranular corrosion raised ridges and blisters, beneath which was a white powder on some of the specimens. The unalloyed specimens were the best of the group. Table 62 shows the loss of weight and maximum penetration of the thin aluminum specimens, exposed approximately 10 years, and similar data on zinc and iron for comparison. None of the thin materials was satisfactory for use unprotected in the corrosive soils to which they were exposed.

TABLE 62.—*Loss of weight and maximum penetration of zinc and aluminum exposed for 10 years.*

Duration of exposure (years)		10.16		10.08		10.05		10.73		10.55	
Material	Identification	Soil 13 Hanford very fine sandy loam		Soil 29 Muck		Soil 42 Susquehanna Clay		Soil 43 Tidal marsh		Soil 45 Unidentified alkali soil	
		Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration	Loss of weight	Maximum penetration
		oz/ft²	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*
Sheet zinc	Z1	3.52	40	4.66	39	0.85	17	2.48	36	[a]D	[b]62+
Cast zinc	Z2	3.47	71	5.37	55	.79	18	2.38	73	9.93	104
Sheet zinc	P	1.89	53	3.85	62+	1.06	20	4.85	40	D	62+
Aluminum	C1	0.086	21	D	62+	0.35	62+	0.18	<6	0.49	46+
Al-Mn-alloy	C2	.38	45+	[c]0.97	62+	.20	14	.22	13	.33	20
Duralumin	C3	D	D	D	D	1.39	62+	.15	<6	[c].56	62+
Open-hearth iron	A	9.92	125+	5.86	62	5.61	70	D	125+	D	125+
Steel+0.2% Cu	S	D	62+	6.91	62+	5.40	59	D	62+	D	62+

[a] D =destroyed by corrosion.
[b] + =1 or both specimens punctured because of corrosion.
[c] Data on 1 specimen only. The other specimen was destroyed by corrosion.

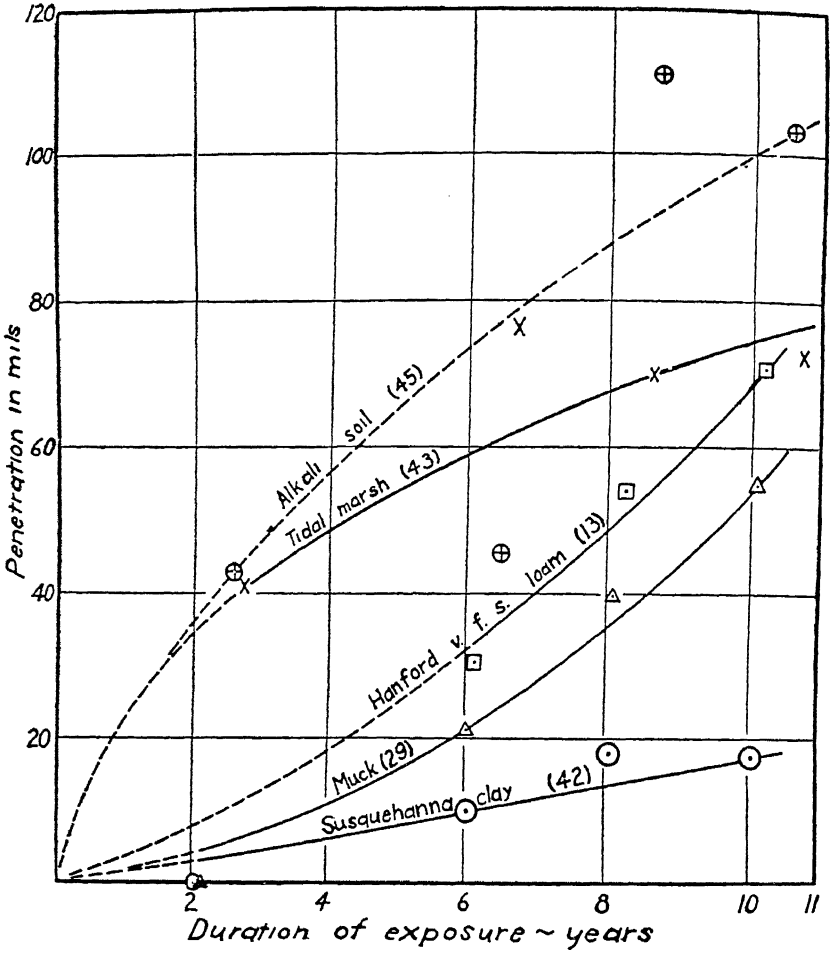

FIGURE 31.—*Relation of the maximum penetration of zinc to the duration of exposure.*

4. ASBESTOS-CEMENT PIPE

The use of asbestos-cement pipe began in Italy about 1916. Since that time it has been used more or less extensively in many constructions in Europe and to a considerable extent in Japan. So few data on the effect of soils on this material are available that the Bureau's 1941 report is reproduced here in full.

Asbestos-cement pipe is a mixture of asbestos fiber and cement. The pipe is built up by a continuous process on a revolving steel mandrel. This is a followed by a curing process. Because asbestos-cement pipe is nonmetallic, it is, of course, not subject to galvanic corrosion, tuberculation, or electrolysis. Pipe of this type is manufactured largely for use in transmission mains and services where the working pressure ranges from 50 to 200 pounds per square inch.

To determine whether or not asbestos-cement pipe is subject to deterioration under soil-exposure conditions, specimens were buried at 15 test sites in 1937. The specimens were 12 inches long and 6 inches in

diameter and had an average wall thickness of 0.72 inch. These specimens were cut from class 150 pipe. Two specimens were removed from each test site at each inspection period after exposure for 2 years and for 4 years. In most soils, especially in the acid soils, there was some softening of the surface of the specimens. However, scratching several specimens indicated that this softening did not extend to greater depths than about one-thirty-second inch below the surface. The softening probably occurred only on the outer layers of the asbestos-cement sheet that were applied to the pipe without pressure during the manufacturing process in order to facilitate the removal of the pipe from the press. The material immediately under the softened outer layers appeared to be of the same density as the rest of the specimen.

TABLE 63.—*Absorption of water by asbestos-cement pipe.*

Soil No.	Specimen No.	Water absorption—percentage gain in weight				
		1 day	2 days	3 days	4 days	14 days
SPECIMENS 2 YEARS UNDERGROUND						
51	41	.....	1.64	1.87	.....	3.68
53	68	.....	2.13	2.74	.....	6.75
55	149	.....	1.86	2.35	.....	6.76
56	39	.....	.86	.97	.....	1.56
58	21	.....	3.08	3.86	.....	7.49
60	71	.....	5.21	6.26	.....	10.18
61	12	.....	1.13	1.36	.....	2.79
62	56	.....	1.55	1.81	.....	3.05
63	1	.....	1.50	1.97	.....	4.25
64	111	.....	1.15	1.31	.....	2.70
65	121	.....	1.58	1.69	.....	.....
66	99	.....	1.11	1.37	.....	.....
67	131	.....	1.00	1.25	.....	3.99
69	89	.....	1.96	2.48	.....	4.42
70	101	.....	2.05	2.40	.....	5.10
SPECIMENS 4 YEARS UNDERGROUND						
53	67	1.69	2.26	.....	3.04	.....
55	147	1.75	2.58	.....	3.80	.....
56	31	.....	.....	.....	.....	.....
58	26	2.53	3.14	.....	3.57	.....
60	74	.....	.....	.....	.....	.....
61	13	1.37	1.54	.....	1.80	.....
62	57	2.45	3.77	.....	5.22	.....
63	9	.....	.....	.....	.....	.....
64	119	.82	1.02	.....	1.18	.....
65	128	.....	.....	.....	.....	.....
66	97	1.85	2.04	.....	2.34	.....
67	133	1.35	1.77	.....	2.11	.....
69	87	2.14	2.61	.....	3.24	.....
70	109	.....	.....	.....	.....	.....
UNBURIED SPECIMENS						
.....	2	.....	4.73	5.69	.....	.....
.....	3	.....	5.96	7.26	.....	.....

The specimens of asbestos-cement pipe removed after exposure of 2 and of 4 years were stored and were not subjected to physical tests until two years after the removal of the longer-exposed specimens, that is, until the specimens had been in storage for 4 and for 2 years, respectively. Then these specimens, together with five specimens which were obtained from the manufacturer at the same time as the others but which had not been buried, were subjected to several tests to be described.

Whether they were affected by the long periods during which they were in storage cannot be determined. Before crushing and bursting tests were made the specimens were immersed in water for at least 48 hours.

(a) WATER-ABSORPTION TEST

Weighed air-dried specimens were immersed in water at room temperature for 2 to 14 days, after which they were removed and wiped with a damp cloth and reweighed. Water absorption was expressed as the percentage gain in weight. The results are tabulated in table 63.

There is no evident consistency in the amount of water absorbed by the specimens as a group, or by the individual specimens buried in the same soil and removed during different periods. Figure 32 shows some of the representative curves obtained from the data. The curves

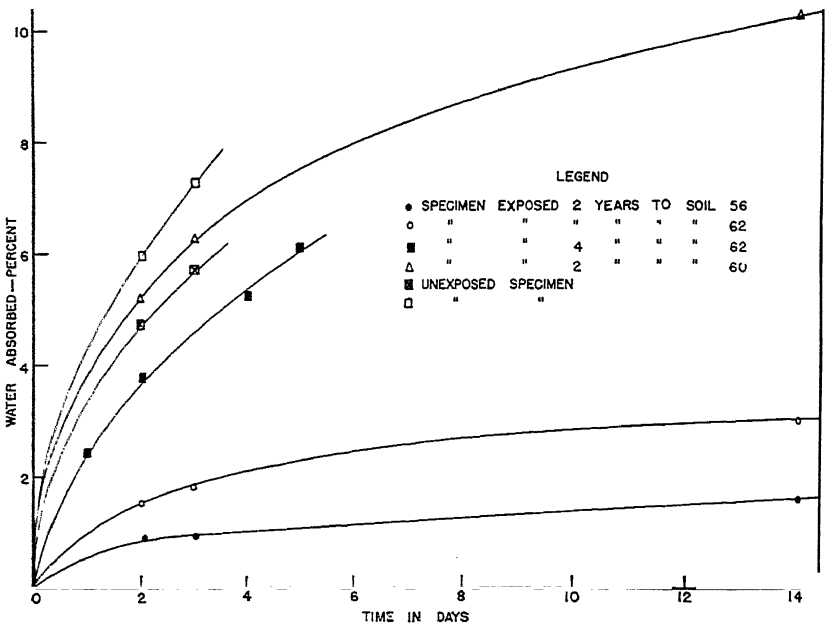

FIGURE 32.—*Percentage of water absorbed by asbestos-cement specimens.*

indicate that the unburied specimens absorbed more water than did the buried specimens, with the possible exception of the specimen buried 2 years in soil 60. The curves also indicate that the specimens were not saturated when tested.

(b) CRUSHING TEST

The crushing tests were made on 5¾-inch lengths of pipe prepared by cutting in half each specimen that had been used for the water-absorption tests. After being air-dried these sections were immersed in water for 48 hours. The tests were made by using three-edge bearings according to the method described in the Federal specifications for asbestos-cement pipe. The load was applied at a uniform rate of approximately 1,000 pounds per minute until failure of the pipe occurred. In testing the specimens, the two sections from the same specimen were

placed under the hydraulic jack in such a way that the parts of the sections receiving the maximum stress were at an angle of 90 degrees to each other.

The crushing strength in pounds per linear foot for each of the sections was calculated. The results of these tests are given in table 64 for the specimens exposed to the soil and for the unexposed specimens. No evident correlation is shown between the values for the crushing strength and the age of the specimens either in individual soils or in any group of soils.

TABLE 64.—*Results of crushing tests on the asbestos-cement specimens exposed to various soils and on the unexposed specimens.*

Soil No.	Sample	Specimens 2 years underground			Specimens 4 years underground		
		Minimum wall thickness	Crushing strength	Apparent specific gravity	Minimum wall thickness	Crushing strength	Apparent specific gravity
		in.	*lb per linear ft*		*in.*	*lb per linear ft*	
51	*a*	0.76	12,160	1.90	.....	.....	.....
	b	.76	12,720	1.90	.....	.....	.....
53	*a*	.72	13,910	1.90	0.70	11,400	1.92
	b	.72	14,400	1.96	.70	10,290	1.90
55	*a*	.69	13,200	1.86	.70	12,590	1.83
	b	.69	11,070	1.78	.70	13,160	1.87
56	*a*	.71	12,930	1.94	.70	12,380	1.86
	b	.71	13,350	1.94	.70	12,800	1.88
58	*a*	.71	11,970	1.89	.74	12,240	1.84
	b	.71	13,550	1.89	.74	12,290	1.91
60	*a*	.70	12,730	1.88	.73	12,670	1.91
	b	.72	11,520	1.82	.73	11,580	1.90
61	*a*	.73	14,600	1.90	.67	9,840	1.99
	b	.73	15,270	1.89	.67	9,550	1.98
62	*a*	.73	17,060	1.94	.71	12,980	1.91
	b	.73	14,240	1.92	.71	12,980	1.90
63	*a*	.77	17,600	1.80	.71	14,990	1.92
	b	.77	17,150	1.86	.71	14,980	1.92
64	*a*	.72	15,400	1.93	.73	14,640	1.95
	b	.72	13,430	1.96	.73	15,940	2.00
65	*a*	.71	15,560	1.92	.73	13,290	1.95
	b	.71	16,400	1.92	.73	13,040	1.94
66	*a*	.72	14,470	1.95	.69	14,160	1.88
	b	.72	14,530	1.97	.69	13,210	1.87
67	*a*	.73	15,900	1.94	.70	11,650	1.92
	b	.73	15,400	1.94	.70	10,640	1.83
69	*a*	.70	13,100	1.88	.71	11,920	1.86
	b	.70	11,000	1.82	.71	11,540	1.84
70	*a*	.70	12,400	1.91	.73	15,440	2.02
	b	.70	13,960	1.94	.73	13,080	1.99
UNEXPOSED SPECIMENS							
4	*a*	.....	.....	.....	0.70	9,940	1.92
	b	.....	.....	.....	.70	10,270	1.90
5	*a*	.....	.....	.....	.71	11,840	1.90
	b	.....	.....	.....	.71	10,530	1.93
Average of unexposed specimens	.....	.....	.....	.....	.70	10,640	1.91

(c) BURSTING TEST

For the bursting tests the second of the pair of specimens removed from each test site at each inspection period was immersed in water for a minimum of 48 hours, and placed in the hydrostatic-pressure testing apparatus shown in figure 33. Internally fitting rubber cups were used to close the ends of the pipe. The apparatus was so designed that the pipe was not subjected to end compression during the test. After filling the pipe under test with water, the entrapped air was allowed to

escape, and the pressure was increased at an approximate rate of 10 pounds per square inch per second until the pipe failed. The pressure gage employed was calibrated before the series of tests.

Many samples failed by a small piece splitting out at one end with the extension of a crack from this point along the entire length of the specimen. The others failed by cracking in one or two places along the

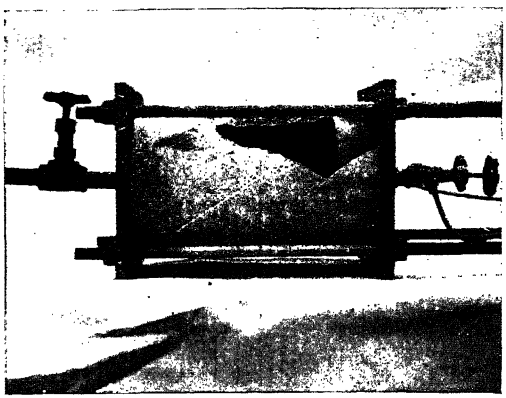

FIGURE 33.—*Bursting-test apparatus.*

entire length of the specimen. In all but three cases, a crack went through a hole, 3/16 inch in diameter, near one end of the specimen, which was used to hold the identification tag. Here again there is no evident correlation between the bursting pressure and the age of the specimens either in individual soils or as any group of soils (see table 65).

TABLE 65.—*Results of bursting tests on the asbestos-cement specimens exposed to the various soils and on the unexposed specimens.*

Soil No.	Specimens 2 years underground			Specimens 4 years underground		
	Minimum wall thickness along fracture	Bursting pressure	Apparent specific gravity	Minimum wall thickness along fracture	Bursting pressure	Apparent specific gravity
	in.	*lb/in.²*		*in.*	*lb/in.²*	
51	0.71	995	1.89	.....	.....	.....
53	.75	1,140	1.83	0.71	1,010	1.84
55	.72	1,085	1.87	.72	1,100	1.77
56	.70	995	2.00	.73	1,050	1.84
58	.73	1,140	1.76	.71	925	1.90
60	.71	1,010	1.76	.72	1,165	1.85
61	.71	1,205	1.92	.71	1,065	1.94
62	.73	1,095	1.97	.70	1,125	1.78
63	.75	1,175	1.84	.74	1,150	1.88
64	.67	1,100	1.98	.74	1,150	1.94
65	.69	935	1.76	.70	1,070	1.84
66	.75	1,215	1.93	.71	1,240	1.89
67	.72	1,030	1.86	.73	1,105	1.82
69	.74	1,255	1.93	.68	1,215	1.89
70	.72	1,155	1.80	.77	1,285	1.84
UNEXPOSED SPECIMENS						
1	.....	.....	.....	0.71	995	1.81
2	.....	.....	.....	.72	940	1.88
3	.....	.....	.....	.73	970	1.93
Average of unexposed specimens	.....	.....	.....	.72	968	1.87

(d) APPARENT SPECIFIC GRAVITY

Samples from the specimens upon which the crushing and bursting tests had been made were dried in an oven at about 110° C for 18 hours, then cooled to room temperature, and the weight of the dry sample determined. The samples were then immersed in water for a period of 24 hours, and the weights in the wet condition were determined in air and then submerged in water. From the weights of the dry samples and the volume of water displaced, the apparent specific gravities of the specimens shown in tables 64 and 65 were calculated. With few exceptions, the specific gravities of the specimens fall between the values 1.80 and 2.00.

(e) COMPARISON OF DATA FROM VARIOUS TESTS

Analysis of the data in tables 63 to 65 fails to bring out any correlation between any of the tests. The bursting- and crushing-test data for the specimens exposed for 2 and for 4 years do not show any evident differences. In some soils the 2-year specimens appear superior to the specimens exposed 4 years, and in other soils the reverse is true. No systematic differences between specimens exposed to different soil conditions can be detected.

TABLE 66.—*Condition of parkway cable exposed 10 to 16 years.*

G = good.
F = fair.
B = bad.
D = destroyed.
M = metal attack.
P = pitted.
R = rusted.
SR = slightly rusted.
H = 1 or more holes.
TW = thin white corrosion product on lead sheet.
W = white corrosion product on lead sheet.

[All steel is zinc-coated]

Soil No.	Duration of test	Outer fabric	Inner fabric	Outer steel	Inner steel	Lead sheath
	Years					
1	11.65	F	G	R	G	G
2	15.48	.....	G	M	M	TW
3	10.02	D	F	P	R	G
5	15.56	G	G	P	SR	TW
6	15.53	F	G	P	M	TW
7	16.94	G	G	P	SR	P
9	15.89	B	G	M	R	W
10	11.95	D	G	P	R	TW
12	15.59	.....	G	M	M	W
16	12.00	D	G	P	SR	TW
17	15.75	F	G	M	M	TW
18	11.71	B	G	R	SR	TW
19	11.63	F	G	R	G	TW
24	11.95	F	G	G	G	G
25	11.67	F	G	SR	G	TW
26	15.90	F	G	M	SR	TW
28	9.60	D	G	P	P	TW
29	10.08	B	F	P	G	TW
30	17.04	F	G	M	SR	TW
31	15.73	B	G	P	M	TW
32	11.66	D	G	R	G	TW
34	12.00	F	G	SR	SR	TW
35	10.16	F	G	P	G	TW
36	15.69	F	G	M	M	TW
37	12.04	B	G	SR	SR	TW
38	15.82	F	G	PH	R	TW
39	12.00	F	G	SR	G	TW
41	17.41	B	G	P	SR	TW
43	12.02	B	G	R	SR	G
45	11.73	B	F	R	R	G
46	12.00	D	G	R	R	TW
47	17.43	G	G	M	SR	W

However, the data do indicate that the asbestos-cement pipes generally gained strength during exposure to the soil, and that the softening observed on the outer layers of the specimens did not penetrate deeply. For only two specimens are the values for the bursting pressure less than the maximum value of the unexposed specimens, and in only one soil are both values of the crushing strength for the exposed specimens less than the average value of the unexposed specimens. It is probable that during exposure of asbestos-cement pipe to the soil, a curing process takes place which tends to increase the strength of the pipe, but there is no indication that the pipe is any stronger after 4 years of exposure than after 2 years of exposure.

5. PARKWAY CABLE

Parkway cable consists of one or more conductors so insulated and protected that the cable can be laid in a trench without further protection against moisture or mechanical injury. The cable tested consisted of a single rubber covered copper conductor with a lead sheath. Over the sheath was a wrapping of fiber treated to prevent rotting. This was surrounded by two spiral wrappings of zinc-coated steel tape. Over the tape was a wrapping of jute or similar material impregnated with a bitumen. When bent sharply the strands of fiber would separate. Table 66 shows the condition of the several parts of the cable buried for from 10 to 17 years. In no case was the usefulness of the cable impaired.

VIII. RESULTS OF FIELD TESTS ON PROTECTIVE COATINGS

1. METALLIC COATINGS

(a) ZINC

As was shown in an earlier section, zinc corrodes under many soil conditions. It is a sacrificial coating first recommended for protecting iron by Sir Humphrey Davey [65] in 1825.

Zinc applied by the hot-dip methods is very extensively used for the protection of small-diameter underground pipes, especially those used for water services. The coating consists of an outer layer of nearly pure zinc and one or more layers of zinc-iron alloy, all of which are anodic to iron and steel and tend to reduce the rate of corrosion of the base metal if small areas are exposed.

The National Bureau of Standards included galvanized pipe in its 1924 burials, and 2 years later undertook to determine whether or not the composition of the iron to which the zinc was applied affected its protective value. The results of the tests indicated that any effect of the differences in these base materials was too small to be shown by the test methods employed, and from this it may be inferred that they are too small to be of any importance under service conditions.

An attempt was also made to determine whether or not the rate of corrosion of galvanized specimens was affected by the thickness of the alloy layer by testing coatings of approximately the same weight applied to No. 16 and No. 18 U. S. Standard Gage Bessemer sheet in 5 soils. Because of the uncontrolled variables involved or because such differences in the thickness of the alloy layer as were produced did not greatly affect the protective value of the coating, no difference in the protective value of the two coatings was found. The determination of the effect of the thickness of the alloy layer requires a closer control of

the factors affecting corrosion than can be obtained under normal field conditions and it can best be solved by laboratory experiments.

Table 67 recalculated from Research Paper RP982 [66] shows the corrosion of galvanized pipe and sheet exposed for approximately 10 years to 43 soils. The losses have been recomputed as total losses per square foot, as a rate implies that the corrosion is proportional to the time of exposure which is not true of coated metals exposed to soil. To show the effect of the coating, the ratio of the average loss of the galvanized sheets to the loss of the unprotected pipe has been computed. Of course this ratio is different for different soils and would change with the thickness of the coating and the period of exposure.

Figure 34, devised by Ewing, presents the data graphically. The length of the heavy lines or horizontal columns shows the weight of the coatings plotted on the same scale as the loss of weight. Along these columns and their extensions the condition of each specimen has been correlated with the loss of weight of the specimen.

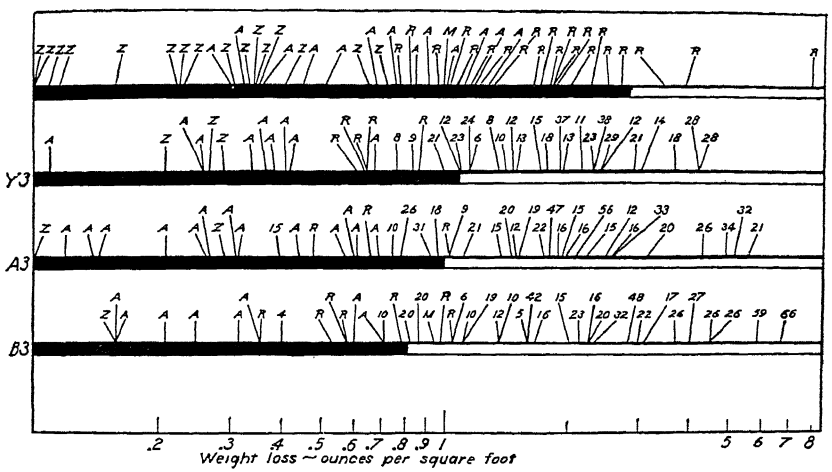

FIGURE 34.—*Correlation between losses of weight and condition of galvanized specimens as determined by inspection.*

The specimens are 10 years old. Where figures appear, they are the rates of penetration of the maximum pit, in mils per year. Where letters appear, they have the following meanings:

Z = Zinc continuous over specimen.
A = Blue or black alloy layer exposed over at least part of specimen.
R = Rusted or bare steel exposed.
M = Shallow metal attack; no pit as great as 10 mils total depth.

The heavy black lines indicate the thickness of the coating on the same scale as for the loss of weight.

It will be noted that with few exceptions, which may possibly be accounted for by thin spots in the coatings, the loss of weight at which rusting appears corresponds closely to the weight of the coating. This may be interpreted as indicating that corrosion of the base metal did not begin until nearly all of the zinc and zinc-iron alloy had been destroyed. The figures along the columns are maximum pit depths. They start near the ends of the solid columns. It will be noted that the heavy double coating prevented all pitting during the 10 years of the test but that rusting had begun in several soils. This indicates that the protective value of this coating is on the average approximately 10 years. The data do not show whether the rate of penetration of galvanized specimens that have begun to rust is as high as for ungalvanized specimens.

TABLE 67.—*Corrosion of galvanized pipe and 16-gage steel sheet with nominal 2-ounce coatings*

[The numbers in parentheses are the weights (oz/ft²) of the coatings.]

pecimen.
er exposed over at least a portion of specimen.
:posed.
no pits as great as 10 mils—total depth.

ype	Duration of test	Rates of loss of weight (oz/ft²)						Ratio[c]	Condition or maximum penetration (in mils)				
		Pipe	Sheet				Bare[b]		Pipe[d],	Sheet			
		A (2.82)[a]	A3 (0.99)	B (0.81)	Y3 (1.07)	Average			B (1.81)	A	A3	B	Y3
	Years												
.....	10.66	2.92	4.62	4.79	4.46	4.62	10.20	0.45	27	R	28	28	30
.....	9.92	0.35	0.44	0.58	0.29	0.44	.....	.....	M	Z	A	R	Z
.....	10.09	.41	.48	.72	.62	.61	3.96	.15	M	Z	R	10	R
.....	10.62	1.94	1.85	1.76	2.05	1.89	.....	.....	R	R	23	17	14
.....	10.17	1.82	2.50	3.03	2.45	2.66	.....	.....	.....	R	12	22	12
r loam.....	10.16	0.12	0.27	0.25	0.09	0.20	.....	.....	.....	Z	A	A	Z
.....	10.48	2.62	2.69	2.36	3.04	2.70	.....	.....	R	R	17	17	22
.....	10.63	0.78	0.65	0.56	0.39	0.53	5.55	.10	R	Z	A	R	A
.....	9.48	1.10	.87	.78	1.08	.91	.....	.....	R	A	29	19	23
e.....	10.62	1.29	1.74	1.71	1.75	1.73	.....	.....	A	R	16	24	12
.....	10.55	0.90	0.42	0.91	1.15	0.83	1.79	.46	.....	A	16	21	13
m.....	10.17	.....	.33	.96	0.26	.52	.....	.....	A	.....	A	M	A
ly loam.....	10.16	[f] .87	2.23	.37	1.37	1.32	.....	.....	.....	R	15	R	8
.....	10.64	.26	0.33	.34	0.68	0.45	5.00	.09	A	Z	A	A	R
.....	10.06	.35	.29	.60	.21	.37	.....	.....	.....	Z	Z	A	Z
n.....	10.04	.99	1.46	2.04	1.78	1.76	6.44	.27	Z	M	20	15	18
.....	10.57	3.64	5.90	3.92	3.89	4.57	.....	.....	R	R	22	27	19
.....	10.51	0.68	0.82	1.16	1.04	0.67	3.30	.20	A	Z	27	20	22
.....	10.67	1.22	2.10	2.40	1.56	2.02	5.01	.40	R	R	17	21	13
.....	9.93	1.19	2.04	2.28	2.37	2.23	7.16	.31	.....	R	56	32	29
.....	10.16	9.60	3.64	2.64	6.38	4.22	25.66	.16	.....	68	37	21	41
ly loam.....	10.63	[f] 0.26	0.13	0.17	0.04	0.11	.....	.....	Z	Z	A	A	Z
.....	10.65	.36	1.09	1.03	.92	1.01	.....	.....	.....	Z	10	R	R
.....	10.48	.71	0.78	1.09	.80	0.89	.....	.....	A	A	10	6	8
.....	10.08	.92	1.49	1.37	.84	.93	.....	.....	.....	A	12	10	9

be	9.60	f 1.96	4.73	6.41	2.22	4.45	16.32	.27	.....	R	33	63	22
.....	10.08	f 5.98	5.19	4.48	4.24	4.64	14.79	.31	30	R	32	26	28
.....	10.51	0.47	1.58	1.42	1.48	1.49	.....	.....	12	A	20	13	11
.....	10.04	f .16	0.05	0.17	0.05	0.09	.....	.....	.....	Z	Z	A	Z
.....	10.71	f .60	.61	.62	.72	.65	3.04	.21	R	R	A	R	A
.....	10.65	1.83	2.00	4.27	1.58	2.62	11.96	.22	.....	R	17	29	14
.....	10.16	0.30	0.70	1.07	0.43	0.73	.....	.....	A	A	A	R	A
.....	10.05	.23	.14	0.43	.34	.30	.....	.....	.....	Z	A	4	A
.....	10.04	2.03	3.15	3.06	3.02	3.08	8.54	.36	.....	R	20	17	14
ıdy loam	10.62	f 0.21	0.16	0.22	0.12	0.17	.....	.....	.....	Z	A	A	A
.....	10.08	.93	2.20	2.22	2.14	2.19	7.48	.29	R	R	47	48	38
.....	10.52	.54	0.27	0.38	0.27	0.31	.....	.....	M	A	A	A	A
.....	10.05	.71	.86	.....	.74	.80	10.64	.08	.....	R	21	.....	23
.....	10.73	f 1.38	1.09	6.27	.69	2.68	12.72	.21	25	A	R	63	R
.....	10.52	.....	0.22	0.75	.43	0.47	.....	.....	.....	.....	A	A	A
il	10.55	f 1.84	1.01	1.69	1.79	1.50	13.53	.11	38	R	19	5	16
ıam	10.54	0.17	0.11	0.17	0.28	0.19	4.38	.04	A	Z	Z	Z	Z
ı	10.60	1.06	.70	.83	.69	.74	.....	.....	A	A	R	R	R

ın here is in ounces per square foot of exposed area. It is the average obtained from at least 10 measurements of thickness by the stripping method.
are" are presented the average weight losses of rolled iron and steel specimens buried a similar length of time, i.e., approximately 10 years. These
s.
o" presents the ratio of the average of the sheets to the bare-metal data column, a low figure indicating that the galvanizing was effective in reducing

12 years. They were not weighed before burial so weight losses are not known.
pecimens. The condition or penetration is for the worse-corroded specimen.
f this material. The condition is for the worse of these specimens.

Figure 35 from the report referred to shows in a simpler way the relation of pit depths to loss of weight and in addition correlates these data with the test-site numbers. The ratio of the pit depth to the loss of weight represented by the slope of the curve is proportional to the

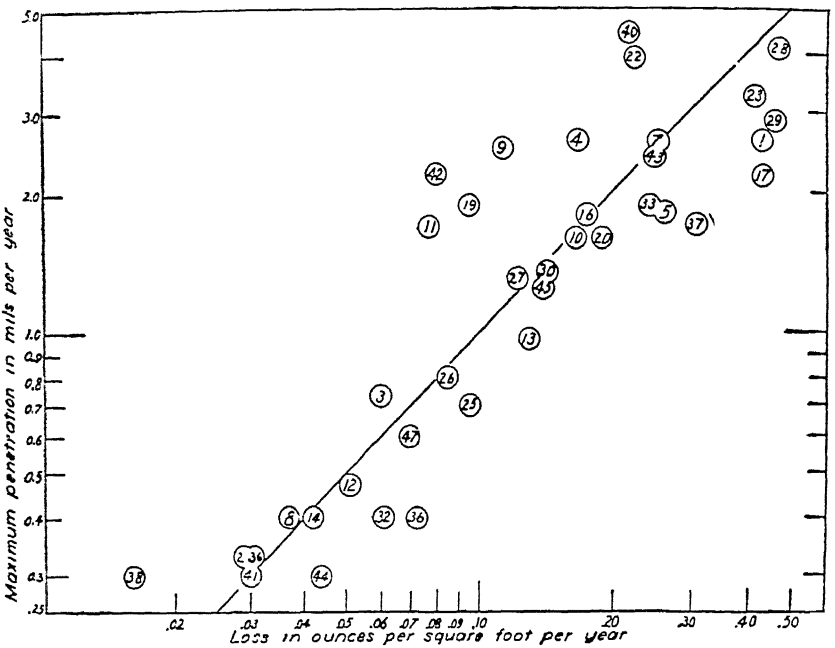

FIGURE 35.—*Correlation between rates of loss of weight and rates of penetration on galvanized specimens.*

pitting factor. As for the unprotected steel, this appears to differ with the soil. In the case of the data represented in figure 35 the dispersion of the data may be affected by variations in the thickness of the galvanizing, which according to Rawdon, [67] on a sheet having an area of 24 square feet and an average coating thickness 2.67 ounces per square foot may have in places as little as 1.79 ounces per square foot or as much as 3.06 ounces per square foot over an area of 18 square inches. Table 68 shows the loss of weight and maximum penetration of galvanized iron pipe carrying a heavier coating exposed to 14 soils for 4 years. A few of the test sites listed in tables 67 and 68 are identical, although they differ in identification numbers. The only known difference in the coatings that may account for the much better performance of the older one is that it was put through the zinc bath twice.

Ewing made an extensive study of the corrosion of gas service pipes, and concluded that galvanized coatings appear to have little value in reducing pipe replacements in congested cities and should not be recommended as a cure for corrosion of services if it is at all severe. He attributes the discrepancy between the performance of the older specimens in the Bureau tests and the performance of galvanized service pipes to electrolysis and galvanic action between the galvanized pipes and ungalvanized mains to which they were connected. These factors are undoubtedly important. It is possible, however, that the galvanized

specimens in table 68 more nearly represent the galvanized material in service. Ewing presented no data on the weight of zinc on the services on which he reported. He suggests that electrolysis and galvanic action might be reduced by insulating the service from the mains. If this is done, a long leakage path between the main and the service should be provided to avoid concentrated corrosion near the insulating point.

TABLE 68.—*Loss of weight and depth of maximum penetration of galvanized and black iron pipe exposed for 4 years.*

Soil		Duration of exposure	Galvanized pipe 3.08 oz/ft²		Black iron pipe		Condition of coating[a]
No.	Type		Loss of weight	Penetration	Loss of weight	Penetration	
		Years	*oz/ft²*	*Mils*	*oz/ft²*	*Mils*	
53...	Cecil clay loam	4.01	1.39	6	2.86	98	2
55...	Hagerstown loam	3.90	[b] 1.22	8	2.60	50	2
56...	Lake Charles clay	3.99	3.89	7	16.03	104	2
58...	Muck	4.01	5.40	[b] 21	8.78	46	3
60...	Rifle peat	3.98	7.18	12	8.06	[b] 38	3
61...	Sharkey clay	4.01	1.46	12	4.99	45	2
62...	Susquehanna clay	4.00	2.28	9	4.30	56	2
63...	Tidal marsh	4.01	2.15	10	9.20	38	1
64...	Docas clay	3.98	1.58	9	5.96	67	2
65...	Chino silt loam	3.99	[b] 2.25	6	4.56	59	3
66...	Mohave fine gravelly loam	3.95	3.32	8	12.31	[c] 145+	2
67...	Cinders	3.98	5.40	45	[d] 37.03	145+	3
69...	Houghton muck	3.98	3.37	11	3.28	20	3
70...	Merced silt loam	3.98	4.52	12	[b] 9.72	118+	3

[a] 1 = coating on more than 50% of surface.
2 = coating on less than 50% of surface.
3 = little or no coating remaining.
[b] Data for individual specimens differed from each other by more than 50%.
[c] + = Hole in 1 or both specimens due to corrosion.
[d] Data for 1 specimen; the other specimen was destroyed.

The extent to which zinc applied to iron protects the iron after it has been exposed by abrasion or corrosion has been studied by several investigators. Mills [68] reported that by casting a zinc collar 4 feet long around 20-foot sections of oil-well tubing the Empire Gas & Fuel Co. extended the life of the tubing from 2 weeks to more than 8 months. Whether this is analogous to the protection afforded by a zinc coating may be questioned.

The first National Bureau of Standards soil-corrosion report [69] describes an experiment in which the zinc was machined off from a 17-inch length of 2-inch galvanized iron pipe to within 2 inches of each end. The pipe was immersed in tap water. Rust formed on the pipe to within 2 inches of the galvanized surface. It has been suggested that the protected lengths depends on the conductivity of the electrolyte.

The way in which a coating of zinc or an attached piece of zinc furnishes protection to iron has been explained in several ways. In some electrolytes a film of corrosion products may afford most of the protection. This is particularly applicable to coatings of zinc. Protection to iron may be afforded by the action of zinc as a sacrificial anode. Bannister [70] has suggested that the protection afforded by zinc plates in a boiler is due to the absorption of oxygen by the zinc. Under favorable conditions zinc coatings could act similarly. Probably each explanation accounts for the protective effect of zinc under some conditions but does not account for it under others.

(b) LEAD

Lead-coated pipe specimens were buried in 41 soils in 1923-24 and in 15 soils in 1932. The maximum and minimum thickness of lead on the 1923 specimens were 2.50 and 0.3 mils, respectively; the corresponding values for the 1932 specimens were 2.97 and 0.5 mils. The last of the 1923 specimens were removed from the less corrosive soils in 1941. Table 69 shows comparable data for these coated specimens and for uncoated steel pipe exposed for somewhat longer periods. Table 70 gives similar data for the same material exposed to more corrosive soils. In the latter table, corrosion is expressed in terms of rates because the steel specimens were exposed for somewhat longer periods. As rates change with the period of exposure, this is not an entirely satisfactory way to report corrosion. However, the table is useful for the comparison of the relative merits of coated and uncoated steel after an exposure of approximately 10 years.

TABLE 69.—*Loss of weight and depth of maximum penetration of 1½-inch lead-coated pipe and Bessemer steel pipe exposed 16 years.*[a]

Soil		Lead-coated		Bessemer steel		Condition of coating[e]
No.	Type	Loss of weight	Penetration	Loss of weight	Penetration	
		oz/ft²	*Mils*	*oz/ft²*	*Mils*	
5	Dublin clay adobe	8.90	104	[b] 7.12	50	3
6	Everett gravelly sandy loam	.36	14	2.03	18	0
7	Maddox silt loam	4.42	145+	5.82	50	3
9	Genesee silt loam	[c] 1.64	[c] 60	5.80	64	2
12	Hanford fine sandy loam	[d] 1.32	[d] 28	6.04	72	2
17	Keyport loam	7.02	49	9.54	41	3
24	Merrimac gravelly sandy loam	.77	28	1.79	16	2
26	Miami silt loam	1.49	48	4.28	42	2
27	Miller clay	4.13	47	10.14	69	3
31	Norfolk sand	.49	28	3.72	43	1
35	Ramona loam	[b] .14	[b] 10	1.51	8	0
36	Ruston sandy loam	1.27	24	4.13	55	3
38	Sassafras gravelly sandy loam	2.17	34	2.30	28	3
41	Summit silt loam	1.27	80	6.87	92	2

[a] Lead-coated pipe buried in 1923-24.
Bessemer steel pipe buried in 1922.
[b] Data on 1 specimen only.
[c] Average of 3 specimens.
[d] Average of 4 specimens.
[e] 0 = coating over entire specimen.
1 = coating on more than 50 percent of surface.
2 = coating on less than 50 percent of surface.
3 = little or no coating left.

TABLE 70.—*Loss of weight and depth of maximum penetration of 1½-inch lead-coated pipe and Bessemer steel pipe exposed for 10 years.*

Soil	Soil type	Rates of loss (oz/ft²)/yr			Rates of maximum penetration (mils/yr)		
		Lead-coated steel	Bare steel [a]	Lead cable sheath [a]	Lead-coated steel	Bare steel	Lead cable sheath
1	Allis silt loam	0.529	0.80	0.173	11.9	5.8	8.1
2	Bell clay	.102	.49	.067	4.0	6.7	1.8
3	Cecil clay loam	.066	.43	.059	3.6	4.5	1.4
4	Chester loam	.239	.52	.177	7.0	6.8	4.0
5	Dublin clay adobe	.597	.45	.135	6.9	3.1	3.8
6	Everett gravelly, sandy loam	.096	.08	.025	2.0	1.4	0.8
7	Maddox silt loam	.207	.37	.....	7.0	2.5	.....
9	Genesee silt loam	.080	.43	.....	5.0	4.5	.....
10	Gloucester sandy loam	.163	.36	.088	6.5	3.2	1.2
11	Hagerstown loam	.071	.16	.034	3.4	4.9	1.2
13	Hanford very fine sandy loam	.064	.....	.....	5.4	.....	.....
14	Hempstead silt loam	.036	.39	.049	4.2	7.1	1.7
15	Houston black clay	.052	.65	.036	3.2	4.4	2.2
17	Keyport loam	.379	.77	.028	4.7	3.3	1.7
18	Knox silt loam	.046	.23	.016	4.6	3.2	1.1
20	Mahoning silt loam	.224	.52	.268	5.3	5.5	4.1
22	Memphis silt loam	.192	.61	.085	7.3	6.6	1.2
24	Merrimac gravelly, sandy loam	.033	.12	.015	2.2	2.1	1.5
27	Miller clay	.231	.63	.067	5.6	4.9	2.4
28	Montezuma clay adobe	.314	1.75	.069	7.8	15.1	0.9
29	Muck	.689	1.61	.343	6.3	12.0	.9
31	Norfolk sand	.028	0.22	.022	1.5	2.5	.5
32	Ontario loam	.072	.32	.028	5.2	4.3	1.5
33	Peat	.537	1.22	.....	7.7	8.9	.....
35	Ramona loam	.011	0.09	.017	[b]	0.4	2.3
36	Ruston sandy loam	.032	.24	.032	1.8	3.9	1.1
37	St. Johns fine sand	.202	.58	.....	6.4	5.6	.....
38	Sassafras gravelly, sandy loam	.053	.22	.025	3.4	2.5	1.7
40	Sharkey clay	.191	.56	.....	6.2	6.6	.....
41	Summit silt loam	.051	.45	.039	5.8	7.6	1.5
42	Susquehanna clay	.092	.95	.....	4.6	7.1	.....
43	Tidal marsh	.726	1.47	.019	18.8	8.7	1.0
45	Unidentified alkali soil	.198	0.79	.021	9.2	6.9	1.7
46	Unidentified sandy loam	.033	.37	.015	4.5	8.8	1.0
47	Unidentified silt loam	.184	.23	.122	6.1	2.4	5.7

[a] Bessemer steel pipe 1½ by 6 inches and commercial lead cable sheath in sheets 20¾ by 3½ by 0.112 inch removed from sites at the same time the lead-coated specimens were removed, were buried, in most cases, 1 or 2 years longer. The figures given are the averages from 2 specimens in the case of the steel and 1 specimen in the case of the lead sheath. The penetration of the sheath was determined by averaging 2 pits, each of which was the deepest on 1 side of the specimen. These pits were, of course somewhat deeper than would be expected on specimens of the same exposed areas as that of the pipe.

[b] No pits.

Table 71 gives similar data for somewhat larger and more heavily coated specimens exposed to other corrosive soils for 9 years. Although, on the whole, the lead-coated specimens showed less penetration than the unprotected steel, their performance can be considered satisfactory in only a limited number of corrosive soils chiefly those containing sulfates. As the data on lead pipe (table 60) show that in a considerable number of soils the penetration is much deeper than the thickness of any coating of lead that has been applied commercially, it seems doubtful that lead coatings should be recommended except, perhaps, in the very limited number of cases where the soil is known not to attack lead.

TABLE 71.—*Loss of weight and depth of maximum penetration of lead-coated and steel pipe exposed for 9 years.*

Soil		Lead-coated [a] CA		Low-carbon steel N		Condition of coating [b]
No.	Type	Loss of weight	Penetration	Loss of weight	Penetration	
		oz/ft²	*Mils*	*oz/ft²*	*Mils*	
53	Cecil clay loam	[c] 1.12	[c] 41	4.09	59	2
55	Hagerstown loam	0.76	44	3.82	59	1
56	Lake Charles clay	20.73	[d] 145+(7)	28.76	154+(7)	3
58	Muck	14.85	[e] 91	16.24	[e] 110	3
59	Carlisle muck	1.07	[f] 21	4.70	[f] 40	1
60	Rifle peat	[f] 7.07	50	16.72	[e f] 27	3
61	Sharkey clay	3.89	50	5.78	[f] 96	2
62	Susquehanna clay	3.64	59	6.65	[f] 87	3
63	Tidal marsh	[c] 3.52	[c] 145+	[f] 9.03	54	2
64	Docas clay	2.10	73	[g] D	154+(5, 7)	2
65	Chino silt loam	3.22	72	12.86	112	2
66	Mohave fine gravelly loam	3.39	57	18.56	154+(5, 7)	2
67	Cinders	D	145+(5, 7)	[h] 58.39	154+(2, 5, 7)	3

[a] This coating was 0.00144 inch thick and contained 1 percent of tin.
[b] 1 = coating on more than 50% of surface.
2 = coating on less than 50% of surface.
3 = little or no coating left.
[c] Data for only 1 specimen.
[d] + = 1 or both specimens punctured. A number in parentheses after the pit depth indicates that 1 of both specimens were punctured in previous removals, i.e., (5) indicates a puncture after 5 years, etc.
[e] Uniform corrosion—no reference surface left on pipe.
[f] Data for individual specimens differed from the average by more than 50%.
[g] D = both specimens destroyed by corrosion.
[h] Data for 1 specimen only; the other specimen was destroyed.

(c) ALUMINUM (CALORIZED)

A calorized coating is an alloy of aluminum with the base metal [67]. It was developed primarily for the purpose of preventing scaling when the metal is subjected to high temperatures. The aluminum oxide, which develops on the surface of calorized materials, was considered as a possible protection against soil corrosion. There are two processes of calorizing. one known as the powder or dry process; the other as the dip. or wet, process. Specimens of pipe calorized by each process were placed in seven soils in 1924. Table 72 gives the rates of corrosion of the calorized specimens, together with the corresponding data for unprotected steel after 10 years of exposure.

In all cases the calorized specimens lost less weight and, with one exception, were pitted at a lower rate than the unprotected pipe in the same soils. In five of the six soils, the powder-calorized pipe was pitted at a lower maximum rate than the dip-calorized pipe, whereas in five of six soils the dip-calorized pipe lost less weight than the powder-calorized pipe. It is thus apparent that the powder-calorized coating was more effective in reducing pitting, although it allowed a greater loss of weight than the dip-calorized coating.

The thickness of the coating on both types of calorized pipes was measured in several places, by the use of the chord method,[6] potassium ferrocyanide and copper sulfate being applied to distinguish the alloy boundary. The thickness of the coating on both kinds of calorized pipe was found to be reasonably uniform. The thickness of the powder-calorized coating was 2 mils and that of the dip-calorized was 11 mils.

It is evident from table 72 that although, on the whole, calorizing made the pipe more resistant to soil corrosion, the process as applied to

[6] See reference 67 for a description of calorizing processes and the chord method.

TABLE 72.—*Corrosion of calorized steel pipe exposed for approximately 10 years.*

Soil	Soil type	Rates of loss of weight [a] (oz/ft²/yr)			Rates of maximum penetration [a] (mils/yr)		
		Dry calorized	Wet calorized	Bare steel [b]	Dry calorized	Wet calorized	Bare steel [b]
13	Hanford very fine sandy loam..	0.137	0.087	1.24	3.4	4.4	13.0
24	Merrimac gravelly, sandy loam.	.019	.013	0.12	2.4	3.2	2.1
28	Montezuma clay adobe.....	.437	.....	1.75	5.5	.....	15.1
29	Muck.....	.250	.458	1.39	3.4	7.8	9.2
42	Susquehanna clay.....	.452	.088	1.25	7.0	4.2	9.2
43	Tidal marsh.....	.861	.434	1.72	3.1	3.4	7.4
45	Alkali soil (Casper, Wyo.).....	.712	.184	1.23	3.4	4.4	11.9

[a] Average of 2 specimens.
[b] Rates for unprotected Bessemer steel specimens of similar area which were exposed, except in the case of soil 13, for a similar period. The data presented for bare steel in soil 13 are for specimens exposed only 6 years, there being no data available for a longer period.

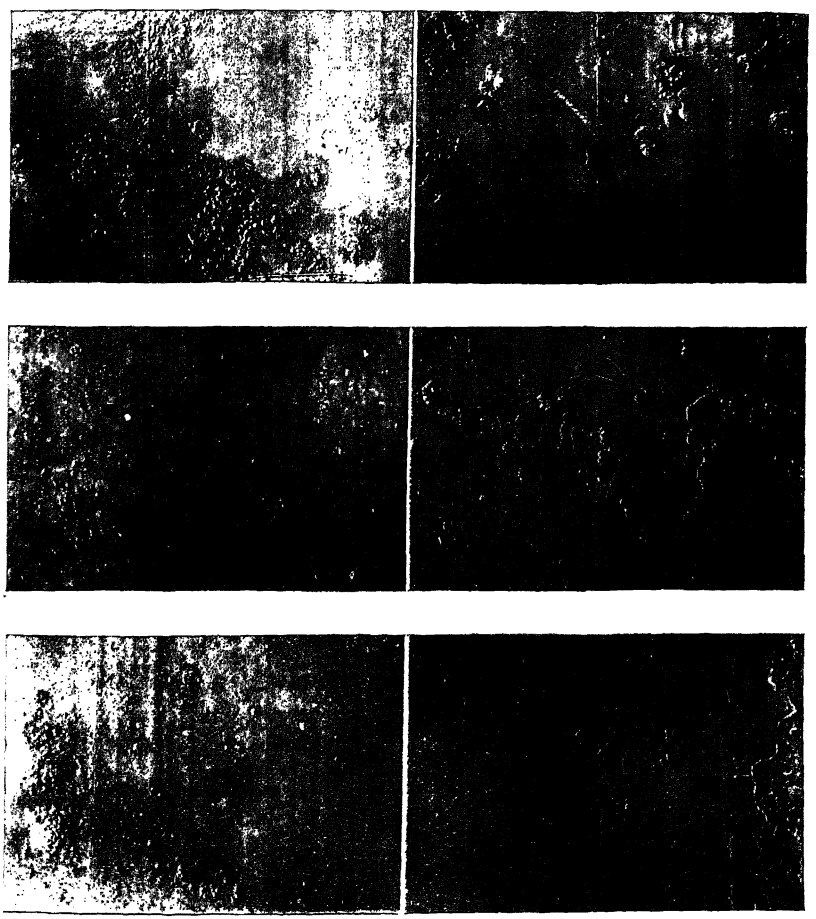

FIGURE 36.—*Panoramic pictures of 2-in. calorized pipe exposed approximately 10 years.*

The specimens on the left are dry calorized; those on the right are wet calorized. The soils to which the specimens were exposed were: top, Hanford very fine sandy loam; center, Muck; bottom, Susquehanna clay.

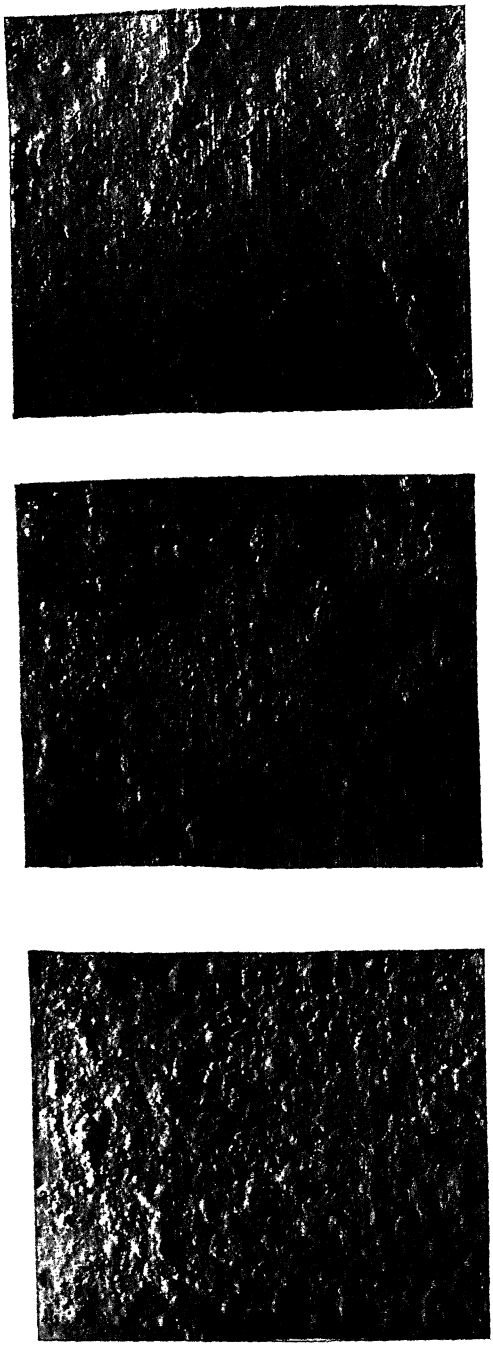

FIGURE 37.—*Panoramic pictures of 2-in. steel pipe exposed with the calorized specimens shown in figure 36.*

Top, Hanford very fine sandy loam; center, Muck; bottom, Susquehanna clay.

the specimens did not prevent pitting in any soil. The rate of pitting and loss of weight are usually high in poorly drained, corrosive soils where the use of a good coating would be economical. The appearance of the calorized specimens from three widely different soils is shown in figure 36. Unprotected steel specimens exposed to the same soils for the same times are shown in figure 37. While these photographs have been selected to show the appearance of more or less typical specimens, they are not presented as the basis for general conclusions.

(d) TINNED COPPER

Table 73 shows the loss of weight and maximum penetration of tinned-copper tube exposed for 4 years and similar data on deoxidized copper pipe exposed at the same test sites for 5 other years. The table shows that, in general, the coating of tin temporarily reduced the rate of loss of weight but, in some cases at least, apparently accelerated the rate of maximum penetration. The coating of tin was quite thin and much of it had disappeared from the specimens from most of the soils.

TABLE 73.—*Loss of weight and depth of maximum penetration of tinned-copper tubes exposed for 4 years and copper pipe exposed for 5 years.*

M, shallow metal attack as indicated by roughening of the surface.
P, definite pitting but no pits greater than 6 mils.
+, one or both specimens contained holes due to corrosion.

Soil		Tinned-copper tube			Deoxidized copper pipe			Condition of coating [a]
No.	Type	Exposure	Loss of weight	Maximum penetration	Exposure	Loss of weight	Maximum penetration	
		Years	*oz/ft²*	*Mils*	*Years*	*oz/ft²*	*Mils*	
53	Cecil clay loam	4.01	0.086	7	5.46	0.15	7	1
55	Hagerstown loam	3.90	.11	M	5.20	.14	P	0
56	Lake Charles clay	3.99	.36	11	5.44	.51	P	2
58	Muck	4.01	.64	39	5.50	1.56	12	2
60	Rifle peat	3.98	4.54	42	5.25	3.82	28	3
61	Sharkey clay	4.01	0.32	18	5.50	0.35	23	2
62	Susquehanna clay	4.00	.081	P	5.47	.26	9	1
63	Tidal marsh	4.01	2.19	[b] 14	5.55	2.45	M	3
64	Docas clay	3.98	0.22	6	5.22	2.22	9	2
65	Chino silt loam	3.99	.12	P	5.26	1.02	10	1
66	Mohave fine gravelly loam	3.95	.23	P	5.28	0.75	7	2
67	Cinders	3.98	20.37	60+	5.26	9.33	54	3
69	Houghton muck	3.98	[c] 0.23	P	.....	.....	.....	1
70	Merced silt loam	3.98	.074	6	.....	.....	.....	1

[a] 0 = coating present over entire surface.
1 = coating present on more than 50% of surface.
2 = coating present on less than 50% of surface.
3 = little or no coating left.
[b] Uniform corrosion—no reference surface left.
[c] Data for 1 specimen only.

Aside from the question of minimum thickness required for protection, a possible cause of failure of tinned copper in soils is the reversal of potential of this couple. As tin is probably anodic to copper under all conditions, corrosion of tin would be expected to protect copper cathodically in the same manner that the corrosion of zinc protects the underlying steel in galvanzied materials. The reversal of potential may be due to the formation of tin-copper alloys, which have been shown under certain conditions to be more cathodic than copper [71].

2. BITUMINOUS COATINGS

(a) SCOPE AND METHODS

The National Bureau of Standards began testing pipe coatings as a means of preventing electrolysis about 1912 [72] and included several pipe coatings in its soil-corrosion tests in 1922. Each time specimens were buried additional samples of coatings were included. The tests indicated that as a means of preventing electrolysis, coatings were unsatisfactory, since they concentrated the current discharged when they failed, as most of those tested did within a short time. In the early tests only one bituminous coating, a cotton fabric impregnated with coal-tar pitch, appeared to be reasonably satisfactory, and the later development of better coatings makes superfluous any detailed report on the early Bureau tests. The Bureau's soil-corrosion investigation and corrosion losses of pipe-line operators led the American Gas Association and the American Petroleum Institute to employ Research Associates to cooperate with the National Bureau of Standards in field tests of pipe coatings. Field tests of coatings were started by the American Gas Association in 1929 and by the American Petroleum Institute in 1930. In general, the plan of testing consisted of applying coatings to sections of pipe or pipe lines located in selected soils and examining the coatings from time to time to determine the effectiveness of the protection which the coatings afforded to the pipe. Four criteria of the performance of the coating were used: 1. Appearance of the coating with respect to adhesion, cracking, distortion, and other physical changes; 2, the pattern test; 3, the conductance or resistance of the coating; and 4, the extent of the corrosion of the protected pipe.

Appearance: An association of coating manufacturers drew up an extensive code [29] for the visual inspection of coatings. This code was followed by both of the Research Associates. The code was intended to yield detailed information free from any bias of the inspector. The amount of data called for this code is too voluminous for presentation to the general reader. The pattern and conductance tests were developed by Ewing [29], Scott [73], and Shepard [74].

Pattern test: The section of coating is washed and painted with a slurry of kaolin or iron-free clay to fill the holes, cracks, and depressions. Over the clay is placed a wet sheet of heavy absorbent paper, such as that used by plate printers as wiping paper. One manufacturer sells it for coating tests as "pinhole papers." Any tough, thick paper that will absorb a considerable quantity of water quickly would be satisfactory. The paper is usually cut in lengths equal to the circumference of the pipe and 1 foot wide. Its position on the pipe is marked, so that if desired, it can be replaced in its original position. Over the paper is wrapped several layers of wet cotton flannel or outing cloth, which is held in place by means of a saddle made of several strips of sheet copper held together at the ends by cross strips. A battery and a voltmeter are connected between the saddle and the pipe for such a time that the product of the voltage multiplied by the time in minutes is 100. If patterns are to be compared, this product must be kept constant. The pipe must be the anode. The paper is then removed from the pipe and washed in a solution consisting of 7 grams of potassium ferricyanide per liter of water. (This is approximately equivalent to 2 tablespoonfuls per gallon of water.) If current has flowed from the pipe through holes in the coating, ferrous hydroxide will be deposited in the paper and this will be turned blue by the solution. The result is one or more blue spots

showing the location and approximate size of the holes in the coating. The pattern serves as a record of the test and assists in the location of the pinholes if they are small.

Conductance test: If the current and voltage are observed during the above test, the resistance or conductance can be computed, provided care is taken to avoid leakage by keeping the coating dry on either side of the pad. After these tests are completed, the coating is removed and the condition of the pipe is determined.

(b) AMERICAN GAS ASSOCIATION TESTS

The American Gas Association, independent coating manufacturers, and the National Bureau of Standards undertook field tests of coatings applied to short lengths of pipe. Forty-two varieties of proprietary bituminous coatings described in table 17 were applied by the makers of the coatings to 20-foot lengths of sandblasted 2-inch steel pipe at a central coating plant. The pipe was then cut into 2-foot lengths, and the ends were closed by tin cans filled with the coating bitumen. The cans served

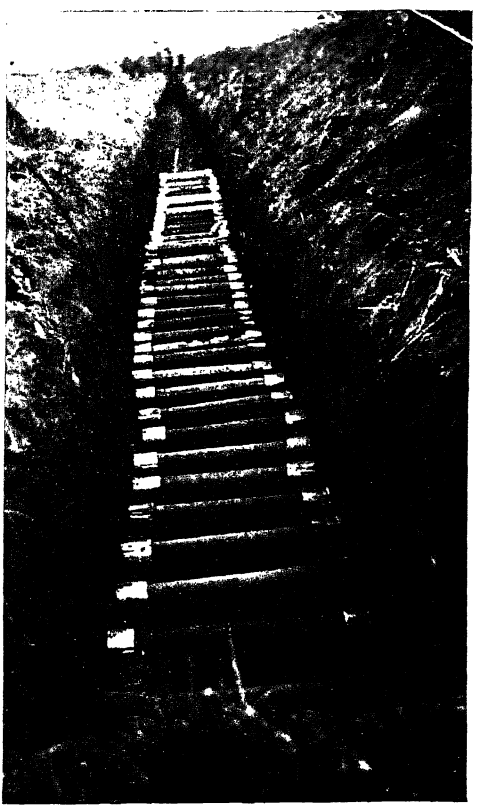

FIGURE 38.—*American Gas Association coatings before burial.*

to keep water out of the pipe, protect the cut ends of the coatings, and support the specimen during shipment. Sixty samples of each material were provided so that four could be placed in each of fifteen soils. The coatings were removed and examined from time to time. Three inspections were made, the last one when the coatings had been exposed for about 4 years.

Figure 38 shows the specimens at one test site before burial. Figure 39, devised by Ewing [75], is a nearly complete report of the results of

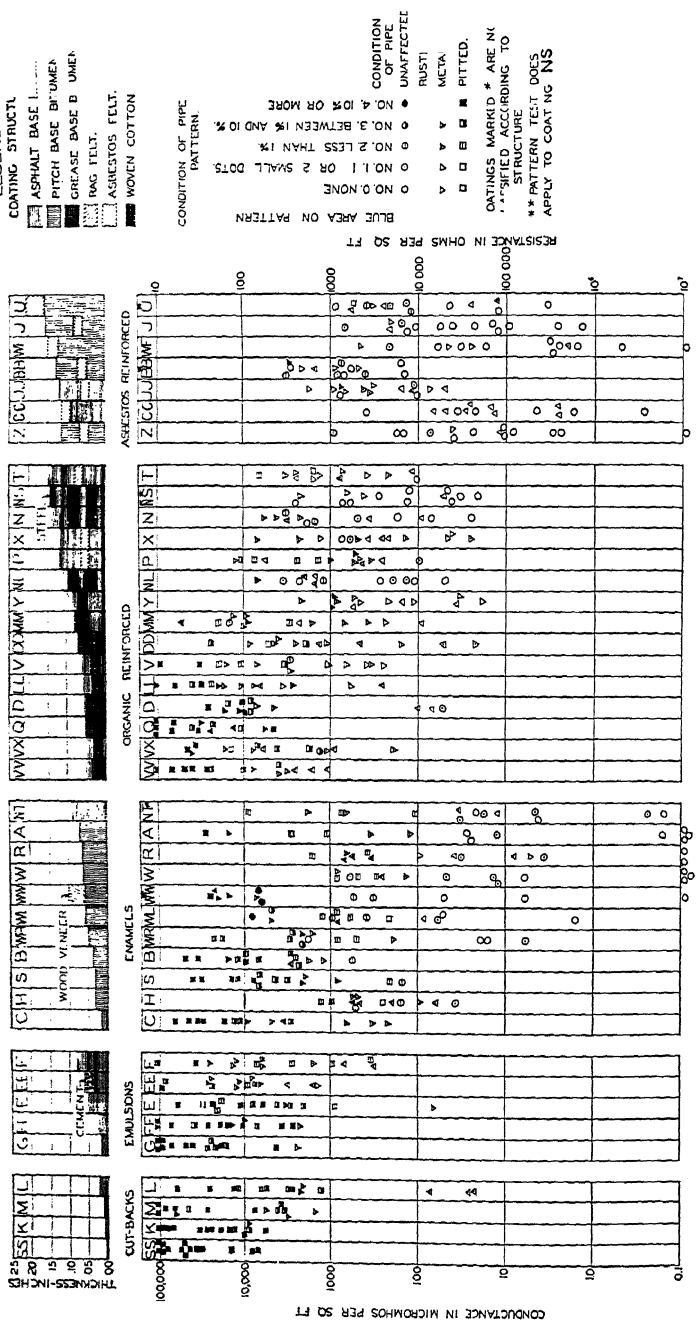

FIGURE 39.—*Results of inspections of American Gas Association coatings after exposure to soils f*

that coal-tar-base materials are more stable and waterproof than asphalt-base materials, but that a good coating could be made from either material, (3) that machine-applied coatings were superior to similar hand-applied coatings and advised against hand-application in the field, and (4) that any organic reinforcement in a coating is a weakness, especially if the bitumen is asphalt. He further advised against the use of any coating that would not afford some protection in poorly drained soils.

(c) AMERICAN PETROLEUM INSTITUTE TESTS

(1) *Sites and Coatings.*—The tests conducted by Ewing were primarily demonstrations of the relative usefulness of certain proprietary coatings. The American Petroleum Institute undertook in 1930 a series of coating tests intended primarily to establish the engineering principles that should govern the design and selection of pipe-line coatings. Substantially the same manufacturers cooperated as in the American Gas Association tests. In addition to the establishment of the engineering principles that should govern the manufacture, selection, and application of pipe coatings, the planners of the Institute tests hoped to determine the applicability of tests of coatings, such as those made by Ewing, to the performance of coatings on pipe lines, and the applicability of the results of corrosion tests, such as the National Bureau of Standards was conducting, to the determination of corrosion of pipe lines.

The design of a series of tests that would accomplish these purposes was a complicated problem, involving many variables and requiring many compromises among the planners, and there was some uncertainty as to the significance of the resulting data. A somewhat detailed description of the manner in which the tests were carried out is, therefore, necessary.

Arrangements were made with 16 pipe-line operators to furnish 1,000 feet of new or substantially new operating line, together with labor for taking up the pipe, applying the coatings, and relaying newly coated pipe. Usually, sections of line where corrosion had occurred were selected, but accessibility of the line and the characteristics of the soil were also considered. In two cases the chosen section of the line had been in the ground a few years and was slightly pitted. In two other cases the soil was so corrosive that the line owners did not wish to take a chance on leaks and therefore laid new pipes parallel to the operating ones. Parts of these new lines were connected electrically to the pipe lines but did not carry oil. One line carried hot oil.

After the pipe had been carefully cleaned, a coating was applied to 30 feet of the line by or under the supervision of the manufacturer of the coating. Another manufacturer applied his coating to the next 30 feet of the line. The next 20 feet of the line was left uncoated as a control, and then two other coatings were applied. The process was continued until half of the new pipe had been used. The other half was then treated similarly. Thus at each site there were two 30-foot sections of pipe line coated with representative samples of each coating, and at one end or the other of each coated section there was a section of bare pipe.

A record was made of the resistivity of the soil opposite each coating to show the uniformity of soil conditions. The thickness of each coating was measured at a number of places to determine its uniformity.

Before the coated pipe was returned to the trench, the coatings were carefully inspected and all discovered imperfections were repaired. To avoid injuries to the coating, great care was exercised in returning the pipe to the trench and in backfilling the trench. The location of the test sites, the soil types, and the profile descriptions are given in Appendix 2.

Tables 14, 15, and 16 give the descriptions of the coatings on the short pipe sections and on the line pipe and their characteristics. It has been suggested by Putnam [76] that alternating bare and coated sections of the line set up a condition of differential aeration that tended to accelerate corrosion under the coatings and to make the uncoated sections cathodic. Such a condition would tend to make the effectiveness of the coatings, as indicated by the condition of the pipe, appear less than it would have been had the entire lines been coated with one material. On the other hand, any stray currents in the earth would be collected and discharged chiefly by the bare sections, and thus the coatings may have been subjected to less than normal electrical stress. Similar arguments might be applied to the comparison of the corrosion of small uncoated pipe with that of the bare sections. However, a careful examination of the data does not disclose any definite evidence to support any of the above criticisms of the tests. This in part may be due to the fact that soil-corrosion data are always more or less variable. Small earth currents flowed in different directions at different times and places, and the soil conditions, as shown by earth resistivity measurements and by visual inspection, were not entirely uniform. It seems probable that, on the whole, the tests were as well conducted as they could have been, and it is doubtful that another test planned in the light of the old one would produce better results.

To determine whether or not the coatings applied to the lines were typical of their classes, and to get some idea of the relative merits of the various available coatings of each class, as well as to compare the results of tests of coatings on operating and on isolated short sections of small-diameter pipe, all the line coatings and all other bituminous coatings offered for test were applied to 2-foot sections of 3-inch boiler type as in the American Gas Association tests, and buried in a separate trench parallel to the operating line. Three specimens of each coating were buried at each test site. The characteristics of these coatings are shown in table 16. To supplement the bare control sections of the pipe lines, and to provide an additional measure of the uniformity of the soil and additional controls, as well as to study the relative rates of corrosion of working lines and small sections of pipe, several 2-foot sections of 3-inch bare steel pipe were buried in the pipe-line trench opposite the bare and coated sections of the line. The condition of the coatings was determined by the methods used in the American Gas Association tests. In the final inspection, the line pipe was marked off into 1-foot lengths, and the depths of the five deepest pits on each section were measured. The American Petroleum Institute tests were under the direct supervision of Scott [73] who reported on the first three inspections of the coatings. The final report on the tests was prepared by K. H. Logan [61] with the advice and assistance of a number of men representing pipe-line operators and coating manufacturers. This is by far the most extensive test of coatings ever conducted.

The report presents a large quantity of data, which permit comparing the coatings in a number of ways. Data are also given regarding the uniformity of test conditions and to enable one to judge the relative

merits of different criteria of coating performance. For the present purpose, however, it is sufficient to present data that will permit a comparison of the coatings on the basis of the condition of the pipe which the coatings were designed to protect. The following section is made up largely of abstracts from the final report.

(2) *Coatings Applied to Pipe Lines.*—Table 74 shows for each line coating at each test site, the average of the deepest pit on each of approximately 20 one-foot sections of coated pipe, the average of the deepest pits on 14 one-foot sections of adjacent uncoated pipe, and the deepest pit on the 3-inch control pipes buried in the same trench and having approximately the same area as 1 foot of line pipe. As an indication of the uniformity of soil conditions, the resistivity of the soil opposite the coated and uncoated sections of the line is also given.

In many cases the same basic coating material was used in two ways, for example, with and without a reinforcement or shield. Table 74 indicates which coatings are to be compared to determine the effect of the reinforcement. For a more complete description of the coatings, see tables 14 and 15.

TABLE 74.—*Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities.*

Coating[2]				Sites[3]																	
				I Temple, Tex.						II Arkansas City, Kans.						III Beaumont, Tex.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control				Line		Control			
Symbol	Thickness (mils)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A																					
C	21	Y	Cutback coal tar	3.6	22	50	49	490	525	...	...	...	...	...	...	208	185	H	H	590	480
A	65	F	Asphalt emulsion	35	29	49	49	475	525	51	50	61	43	1,200	875	233	187	H	H	500	530
2. ENAMELS																					
N	60	G	Coal-tar-asphalt enamel	...	...	...	...	...	...	8.3	59	48	39	1,000	715	73	209	H	H	480	490
K	69	U	....do	...	...	...	...	...	...	30	59	57	39	1,025	715	109	175	H	H	480	415
M	58	...	Coal-tar enamel	29	29	69	49	455	480	33	53	39	52	2,325	900	188	151	H	...	545	585
L	80	H	....do	...	...	...	...	...	...	10	53	49	52	3,275	900	231	175	H	H	525	415
3. MASTIC																					
O	519	...	Asphalt mastic	1.5	21	58	61	500	700	0.25	48	52	46	1,800	1,025	0	151	H	...	360	585
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS																					
Y	29	C	Cutback asphalt	5.8	20	53	48	525	495	...	...	...	...	...	...	...	...	...	...	...	...
F	419	A	Asphalt emulsion	1.2	22	56	49	530	525	...	...	...	...	...	...	...	...	...	...	...	...
G	63	N	Coal-tar-asphalt enamel	...	...	...	...	...	...	1.1	48	60	56	1,225	850	14	185	H	H	500	480
H	81	L	Coal-tar enamel	...	...	...	...	...	...	...	...	...	...	...	...	87	209	H	H	660	490
5. REINFORCED COATINGS																					
B	107	...	Grease	6.0	29	48	49	500	480	20	48	53	56	950	850	...	...	...	...	...	...
S	150	...	Asphalt	29	39	51	...	725	535	22	59	71	65	3,265	3,240	...	...	...	...	...	...
E	151	...	....do	2.4	20	48	48	640	495	5.7	48	55	46	1,525	1,025	...	...	...	...	...	...
Z	201	X	....do	4.8	23	53	46	465	555	19	47	50	78	2,825	1,325	44	100	H	H	355	305
R	143	...	Asphalt enamel	13	21	62	61	625	700	20	59	59	65	965	3,240	15	130	H	159	450	440
U	171	K	Coal-tar-asphalt enamel	7.6	35	66	49	2,740	615	6.1	58	60	53	1,025	690	4.0	130	H	159	475	440
T	351	...	Coal-tar enamel	3.2	39	56	...	825	535	...	...	...	...	...	...	...	...	...	...	...	...
6. SHIELDED AND REINFORCED																					
X	230	Z	Asphalt	3.5	23	51	46	570	555	5.8	47	56	78	1,700	1,325	10	100	H	H	305	305

(See footnotes at end of table.)

TABLE 74.—*Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities*—Continued.

Coating[2]				Sites[3]																	
				IV League City, Tex.						V Preble, Ind.						VI Council Hill, Okla.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control				Line		Control			
Symbol	Thickness (mils)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A																					
C	21	Y	Cutback coal tar	40	64	76	69	1,400	1,750	46	35	50	42	2,000	3,000	25	41	59	44	3,200	3,100
A	65	F	Asphalt emulsion	42	33	71	51	1,300	1,450	61	41	57	37	2,200	2,900	38	40	45	44	2,400	2,450
2. ENAMELS																					
N	60	G	Coal-tar-asphalt enamel	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	36	41	56	65	4,100	5,100
K	69	U	....do	.....	.....	.....	.....	.....	.....	12	35	62	60	2,900	3,000	28	46	60	57	3,150	3,250
M	58	.....	Coal-tar enamel	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	38	36	48	44	2,450	2,600
L	80	H	....do	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	50	44	54	62	1,650	4,750
3. MASTIC																					
O	519	.....	Asphalt mastic	0.2	51	90	95	1,350	1,900	0.05	35	49	60	5,500	3,000	.....	.....	.....	.....	.....	.....
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS																					
Y	29	C	Cutback asphalt	19	52	68	84	1,650	1,500	.....	.....	.....	.....	.....	.....	43	41	49	48	3,900	2,350
F	419	A	Asphalt emulsion	.....	.....	.....	.....	.....	.....	1.7	34	51	38	2,250	3,900	21	41	46	48	3,750	2,350
G	63	N	Coal-tar-asphalt enamel	.....	.....	.....	.....	.....	.....	7.4	34	50	64	3,500	2,250	14	45	60	62	5,000	5,500
H	81	L	Coal-tar enamel	8	53	84	108	1,400	1,750	2.8	34	48	64	2,500	2,250	31	40	54	65	2,600	4,100
5. REINFORCED COATINGS																					
B	107	.....	Grease	11	33	61	51	1,750	1,150	14	34	46	38	5,300	3,900	25	40	50	44	2,175	2,450
S	150	.....	Asphalt	32	40	71	83	1,100	1,150	12	39	46	39	1,950	2,800	.....	.....	.....	.....	.....	.....
E	151	.....	....do	3.7	24	82	51	1,650	1,000	8.6	35	46	46	2,750	3,000	26	47	57	62	4,650	4,000
Z	201	X	....do	6.2	29	76	71	900	900	6.5	45	59	36	4,250	4,000	.....	.....	.....	.....	.....	.....
R	143	.....	Asphalt enamel	12	37	80	84	1,350	1,150	9.9	39	42	39	2,900	2,800	.....	.....	.....	.....	.....	.....
U	171	K	Coal-tar-asphalt enamel	2.6	29	77	71	900	650	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
T	351	.....	Coal-tar enamel	25	37	75	69	1,000	900	.....	.....	.....	.....	.....	.....	27	42	72	50	2,750	3,900
6. SHIELDED AND REINFORCED																					
X	230	Z	Asphalt	2.1	53	65	58	3,000	1,350	3.8	45	46	36	1,800	4,000	.....	.....	.....	.....	.....	.....

See footnotes at end of table.

TABLE 74.—*Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities*—Continued.

Coating[2]				Sites[3]																	
				VII Caney, Kans.						VIII Spindle Top Gully, Tex.						IX Long Beach, Calif.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control				Line		Control			
Symbol	Thickness (mils)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A																					
C	21	Y	Cutback coal tar	27	40	54	52	1,700	1,700												
A	65	F	Asphalt emulsion																		
2. ENAMELS																					
N	60	G	Coal-tar–asphalt enamel	30	60	68	83	1,400	1,500	74	79	H		455	460	0.4	81	80	109	1,500	1,015
K	69	U	....do	19	73	40	48	1,400	1,150												
M	58		Coal-tar enamel	35	60	63	83	1,525	1,500												
L	80	H	....do	25	73	78	48	1,350	1,150	111	89	89		385	345	0.06	62	74	77	1,815	1,090
3. MASTIC																					
O	519		Asphalt mastic	1.2	45	45	50	1,500	1,075	6	89	H		370	345	0.0	94	89	72	1,020	975
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS																					
Y	29	C	Cutback asphalt							85	120	74		355	375	44	106	101	112	1,265	605
F	419	A	Asphalt emulsion							37	93	77		360	360	1.3	93	H	70	1,180	580
G	63	N	Coal-tar–asphalt enamel	1.3	40	69	52	1,600	1,700	6.8	90	H		445	430	0.65	72	87	85	800	925
H	81	L	Coal-tar enamel							129	79	69		310	460	0.05	82	106	86	875	810
5. REINFORCED COATINGS																					
B	107		Grease	19	40	52	44	1,550	1,400												
S	150		Asphalt	27	48	62	57	1,500	1,200	92	104	85		390	370	15	90	99	70	1,025	675
E	151		....do																		
Z	201	X	....do																		
R	143		Asphalt enamel	5.6	70	75	56	1,100	1,125	75	113	H		355	350	13	99	46	72	2,325	845
U	171	K	Coal-tar–asphalt enamel	21	45	70	50	1,350	1,075	96	104	H		290	390	0.0	99	86	72	1,025	845
T	351		Coal-tar enamel	20	100	67	62	900	975	43	135	H		415	385	0.0	58	43	78	1,600	1,345
				11	48	66	57	1,400	1,250	12	135	103		385	385	5.2	80	184	107	1,925	810
6. SHIELDED AND REINFORCED																					
X	230	Z	Asphalt							13	125	79		335	415	2.4	58	77	78	1,240	1,345

(See footnotes at end of table.)

TABLE 74.—*Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities*—Continued.

Coating[2]				Sites[3]																	
				X Mt. Auburn, Ill.						XI Skiatook, Okla.						XIII Bunkie, La.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control				Line		Control			
Symbol	Thickness (mils)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A																					
C	21	Y	Cutback coal tar	23	35	57	58	2,250	1,200	....	....	....	....	....	....	81	99	62	44	440	875
A	65	F	Asphalt emulsion	48	41	70	58	2,600	1,650	....	....	....	....	....	....	106	70	49	39	440	375
2. ENAMELS																					
N	60	G	Coal-tar-asphalt enamel	33	55	75	69	1,800	1,300	36	64	51	40	265	315	....	....	....	....	....	....
K	69	U	....do	16	45	68	60	2,050	1,050	16	107	85	55	525	540	31	74	71	43	425	375
M	58	....	Coal-tar enamel	44	55	60	69	3,000	1,300	102	87	51	44	265	425	....	....	....	....	....	....
L	80	H	....do	23	24	65	50	1,200	1,500	73	87	41	44	590	425	....	....	....	....	....	....
3. MASTIC																					
O	519	....	Asphalt mastic	....	....	....	....	....	....	2.8	64	52	40	1,000	315	0.0	92	46	41	440	465
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A, AND ENAMELS																					
Y	29	C	Cutback asphalt	11	56	77	....	2,000	1,550	....	....	....	....	....	....	78	56	41	41	375	450
F	419	A	Asphalt emulsion	24	46	66	55	1,600	1,450	....	....	....	....	....	....	6.6	52	37	44	375	390
G	63	N	Coal-tar-asphalt enamel	21	35	60	58	1,550	1,200	....	....	....	....	....	....	9.0	56	41	41	400	450
H	81	L	Coal-tar enamel	5.1	45	57	60	1,200	1,050	....	....	....	....	....	....	116	74	49	43	450	375
5. REINFORCED COATINGS																					
B	107	....	Grease	17	46	65	55	2,300	1,450	37	102	88	90	365	210	....	....	....	....	....	....
S	150	....	Asphalt	....	....	....	....	....	....	....	....	....	....	....	....	127	92	54	41	390	465
E	151	....	....do	19	24	72	50	1,150	1,500	46	79	79	101	265	335	120	52	42	44	415	390
Z	201	X	Asphalt	....	....	....	....	....	....	17	107	66	55	875	540	22	53	41	35	440	450
R	143	....	Asphalt enamel	....	....	....	....	....	....	29	71	55	48	715	700	....	....	....	....	....	....
U	171	K	Coal-tar-asphalt enamel	....	....	....	....	....	....	27	56	49	46	775	375	27	99	63	44	390	375
T	351	....	Coal-tar enamel	10	56	85	....	1,500	1,550	3.4	71	59	48	525	700	....	....	....	....	....	....
6. SHIELDED AND REINFORCED																					
X	230	Z	Asphalt	....	....	....	....	....	....	8.6	79	62	101	440	335	2.6	53	40	35	390	450

See footnotes at end of table.

TABLE 74.—*Averages*[1] *of maximum pit depths on coated and corresponding bare pipes with soil resistivities*—Continued.

Coating[2]				Sites[3]											
				XIV Chambersburg, Pa.						XVI Cholame Flats, Calif.					
				Pit depths (*mils*)				Resistivity (ohm-cm)		Pit depths (*mils*)				Resistivity (ohm-cm)	
				Line		Control				Line		Control			
Symbol	Thickness (*mils*)	Associated coating	Character	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare	Coated	Nearest bare	Opposite coating	Opposite nearest bare	Opposite coating	Opposite nearest bare
1. COLD APPLICATIONS: CUTBACKS, C; AND EMULSIONS, A															
C	21	Y	Cutback coal tar												
A	65	F	Asphalt emulsion	26	31	59	50								
2. ENAMELS															
N	60	G	Coal-tar–asphalt enamel												
K	69	U	....do	2.5	36	56	50								
M	58		Coal-tar enamel	21	36	48	50								
L	80	H	....do							60		[4] L		140	
3. MASTIC															
O	519		Asphalt mastic							0.39		L		315	
4. SHIELDED COATINGS: CUTBACKS, C; EMULSIONS, A; AND ENAMELS															
Y	29	C	Cutback asphalt	2.9	32	54	42								
F	419	A	Asphalt emulsion	3.9	28	48	51			40		L		140	
G	63	N	Coal-tar-asphalt enamel							81		H		225	
H	81	L	Coal-tar enamel	2.9	33	62	53								
5. REINFORCED COATINGS															
B	107		Grease	3.5	28	45	51								
S	150		Asphalt	9.7	35	41	46								
E	151		....do	3.3	33	48	53			51		153		210	
Z	201	X	....do							21		H		190	
R	143		Asphalt enamel	1.8	35	59	46								
U	171	K	Coal-tar–asphalt enamel	0.08	32	55	49			20		H		240	
T	351		Coal-tar enamel							1.4		L		180	
6. SHIELDED AND REINFORCED															
X	230	Z	Asphalt	2.4	32	48	49			33		H		235	

[1] Averages are usually based on 20 one-foot sections of coated pipe; 14 one-foot sections bare lines; and the equivalent of 2 three-foot sections of 3-in. bare control pipe.
[2] See tables 14 and 15 for description of coatings.
[3] See Appendix 2 for description of soils.
[4] Original surface gone, making pit-depth measurements inapplicable.

merits of different criteria of coating performance. For the present purpose, however, it is sufficient to present data that will permit a comparison of the coatings on the basis of the condition of the pipe which the coatings were designed to protect. The following section is made up largely of abstracts from the final report.

(2) *Coatings Applied to Pipe Lines.*—Table 74 shows for each line coating at each test site, the average of the deepest pit on each of approximately 20 one-foot sections of coated pipe, the average of the deepest pits on 14 one-foot sections of adjacent uncoated pipe, and the deepest pit on the 3-inch control pipes buried in the same trench and having approximately the same area as 1 foot of line pipe. As an indication of the uniformity of soil conditions, the resistivity of the soil opposite the coated and uncoated sections of the line is also given.

In many cases the same basic coating material was used in two ways, for example, with and without a reinforcement or shield. Table 74 indicates which coatings are to be compared to determine the effect of the reinforcement. For a more complete description of the coatings, see tables 14 and 15.

TABLE 75.—*Summary of conditions of line pipe undercoatings.*

Coating				Total feet inspected	Unaffected		Rusted		Metal attack		Pitted		Depth deepest pit (mils)
Symbol	Thickness (mils)	Associated coating	Character		Total feet	Percent	Total feet	Percent	Total feet	Percent	Total feet	Percent	
1. COLD APPLICATIONS													
C	21	Y	Cutback coal tar	166	2	1.2	9	5.4	16	9.6	139	84.5	[a] 322+
A	65	F	Asphalt emulsion	178	0	0	0	0	3	1.7	175	98.3	[a] 322+
2. ENAMELS													
N	60	G	Coal-tar–asphalt enamel	152	21	13.8	21	13.8	16	10.7	94	62.0	264
K	69	U	....do	183	13	7.2	15	8.2	54	29.6	101	55.0	195
M	58	.....	Coal-tar enamel	151	0	0	0	0	3	2.0	148	98.0	231
L	80	H	....do	157	31	19.8	6	3.8	10	6.4	110	70.1	[a] 322+
3. MASTIC													
O	519	.....	Asphalt mastic	213	154	72.5	39	18.4	14	6.6	6	2.8	38
4. SHIELDED COATINGS													
Y	29	C	Cutback asphalt	164	2	1.2	17	10.4	30	18.3	115	70.0	200
F	419	A	Asphalt emulsion	170	6	3.5	66	39.0	37	21.8	61	35.9	107
G	63	N	Coal-tar–asphalt enamel	202	59	29.3	36	17.9	51	25.3	56	27.8	[a] 322+
H	81	L	Coal-tar enamel	177	76	43.0	7	4.0	9	5.1	85	48.0	240
5. REINFORCED COATINGS													
B	107	.....	Grease	208	0	0	9	4.3	61	29.4	138	66.3	89
S	150	.....	Asphalt	166	0	0	2	1.7	39	23.5	125	75.3	290
E	151	.....	....do	192	9	4.7	17	8.9	70	36.5	96	50.0	197
Z	201	X	Asphalt	228	1	0.4	22	9.7	105	46.1	100	44.1	160
R	143	.....	Asphalt enamel	208	42	20.2	19	9.2	42	20.2	105	50.5	197
U	171	K	Coal-tar–asphalt enamel	218	67	30.8	13	6.0	51	23.5	87	39.9	126
T	351	.....	Coal-tar enamel	175	26	14.9	25	14.3	58	33.1	66	37.7	58
X	230	Z	Asphalt	229	12	5.2	31	13.5	140	61.1	46	20.1	124
Total	.....	.....	.....	3,537	521	14.7	354	10.0	809	22.9	1,853	52.2	.....

[a] Through pipe.

TABLE 76.—*Single deepest pit on 20 feet of coated line pipe after 10 years of exposure.*

U = Unaffected.
R = Rusted.
M = Metal attack.
+ = Hole.

[In mils]

Coating symbol	Test sites [a]													
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XIII	XIV	XVI
1. COLD APPLICATIONS														
C	20	.....	322+	67	137	39	47	.....	.....	51	.....	242	.....	.....
A	91	86	322+	87	107	37	.....	.....	.....	105	.....	128	54	.....
2. ENAMELS														
M	43	69	231	.....	.....	76	57	.....	.....	60	148	.....	45	.....
K	.....	60	195	.....	89	52	84	.....	.....	70	36	166	16	.....
N	.....	45	264	.....	.....	89	65	170	R	61	58	.....	.....	.....
L	.....	52	322+	.....	.....	97	60	148	R	76	151	.....	.....	63
3. MASTIC														
O	R	M	U	U	U	.....	R	38	U	.....	R	U	.....	R
4. SHIELDED COATINGS														
Y	40	.....	.....	73	.....	97	...	126	80	45	.....	120	M	.....
F	M	.....	.....	.....	M	40	...	107	M	68	.....	38	M	103
G	.....	R	118	.....	90	29	R	45	10	35	.....	46	.....	322+
H	.....	.....	211	30	20	45	...	220	R	35	.....	240	53	.....
5. REINFORCED COATINGS														
B	12								36		54			
S	100	55						290				202		
E	12	19								26	117	197		103
Z	22	50	183				18	144			69	132		80
R	51	51	61				67	197			56	....		
U	61	39	40				123	120			126	70		70
T	16					40	27	32		38	27			17
6. SHIELDED REINFORCED COATINGS														
	15	17	22	M	24			121	M	.....	31	M	11	124

[a] See table 19 for location of test sites.

(3) *Coatings Applied to Isolated Short Sections of Small-Diameter Pipe.*—The results of the tests shown in tables 77 and 78 furnish data on 46 coatings applied to 2-foot lengths of pipe having an outside diameter of 3 inches and supplement Ewing's tests on similar and occasionally identical coatings or coating materials. From a technical point of view, the data on the short lengths of pipe are of interest because they permit a comparison of two methods of testing coatings.

TABLE 77. *Depth[1] of the deepest pit on short pipe sections.*

Coating[2]				Test sites[3]														
Symbol	Thickness (mils)	Associated coating[4]	Character	I. Temple, Tex.	II. Arkansas City, Kans.	III. Beaumont, Tex.	IV. League City, Tex.	V. Preble, Ind.	VI. Council Hill, Okla.	VII. Caney, Kans.	VIII. Spindle Top Gully, Tex.	IX. Long Beach, Calif.	X. Mt. Auburn, Ill.	XI. Skiatook, Okla.	XII. Mendota, Calif.	XIII. Bunkie, La.	XIV. Chambersburg, Pa.	XVI. Cholame Flats, Calif.
1. COLD APPLICATIONS																		
ee	45	e	Cutback asphalt	[5] R	R	104	[6] M	M	12	16	88	M	M	38	R	M	R	M
u	47	.....	....do	R	32	112	26	M	12	21	43	67	R	M	[9] U	H	R	M
l	81	.....	....do	R	32	108	M	M	23	13	35	51	M	M	U	23	M	M
zx	12	.....	....do	M	28	10H	26	22	26	32	55	32	R	25	78	H	M	54
b	20	bb	....do	M	17	H	14	41	29	35	67	M	23	M	U	14	M	35
j	15	ppp	Asphalt emulsion	41	27	15H	31	37	32	38	58	77	M	31	31	41H	10	78
ppp	15	j	....do	R	12	5H	32	22	29	24	H	32	R	75	59	H	M	94
fff	37	f, ff	....do	14	24	5H	54	36	29	50	51	21	M	21	35	129	21	48
2. ENAMELS																		
vv	79	.....	Asphalt	R	M	62	22	M	R	M	23	24	M	M	24	25	M	27
w	92	ww	....do	10	80	2H	38	55	27	31	65	M	M	M	17	107	M	65
s	41	ss	Coal-tar asphalt	U	U	U	R	U	16	U	23	22	M	M	U	M	U	24
k	75	kk	....do	R	10	U	U	M	14	R	M	M	U	M	32	M	U	M
t	52	.....	Coal tar	14	22	10H	24	25	31	37	43	24	M	25	R	H	38	77
dd	50	d, ddd	....do	14	M	H	41	U	23	38	45	R	M	56	58	154	M	29
a	54	.....	....do	R	24	114	M	16	23	31	63	76	U	U	U	M	U	M
g	69	p, zz, zzz	....do	R	.....	32	M	U	M	17	18	R	U	U	U	M	U	U
z	72	.....	....do	R	U	H	32	U	12	R	33	U	U	U	U	R	M	U
zzz	77	p, g, zz	....do	M	M	108	22	U	18	15	48	U	U	U	U	U	U	47
p	.....	zz, zzz, g	....do	R	U	51	M	U	20	U	50	U	R	R	R	H	U	U
3. MASTIC																		
h	69	.....	Asphalt	28	M	3H	61	29	25	45	64	44	R	M	U	2H	U	57
qqq	183	.....	....do	14	M	H	U	M	13	11	32	36	M	M	U	109	U	70
nn	337	.....	....do	U	R	30	U	U	U	R	M	R	M	M	U	U	U	U
v	337	.....	....do	U	M	M	U	U	U	U	U	R	U	M	U	U	R	U

x	18	.....	Cutback asphalt	R	M	122	M	M	M	M	39	71	R	14	55	M	U	H
ff	190	f, fff	Asphalt emulsion	U	M	63	M	U	M	R	20	M	M	M	R	23	M	38
ss	[8] 41	s	Coal-tar–asphalt enamel	R	U	U	U	U	M	U	U	U	M	21	U	U	U	U
ddd	[8] 50	d, dd	Coal-tar enamel	U	U	U	M	U	U	U	M	U	R	U	U	U	U	U
zz	[8] 77	g, p, zzz	....do	R	U	U	U	U	M	U	M	U	U	U	U	U	U	U

5. REINFORCED COATINGS

c	72	cc	Cutback asphalt	33	23	112	32	M	15	31	67	R	M	M	M	41	23	M
bb	34	b	Cutback coal tar	12	12	5H	38	30	33	24	37	12	M	M	R	81	R	55
m	89	.....	Asphalt emulsion	M	M	90	M	M	11	M	50	21	M	22	M	37	M	M
f	149	ff, fff	....do	M	M	M	R	M	M	M	M	M	M	M	U	19	M	R
cc	22	c	Grease	14	25	H	M	.....	19	M	21	M	.....	19	47	29	M	28
e	26	ee	....do	M	11	5H	M	M	R	12	17	M	M	14	31	88	20	18
y	144	yy, yyy	Asphalt	R	M	42	M	M	28	24	33	24	M	M	R	H	M	43
pp	138	q, g	....do	M	U	.....	R	M	M	M	20	M	M	M	U	15	M	.....
q	155	pp, qq	....do	M	14	62	M	M	M	M	13	M	M	16	M	22	M	17
n	158	.....	....do	M	M	141	22	R	M	M	19	M	M	10	U	H	U	22
yyy	259	y, yy	....do	U	M	29	M	M	M	M	21	M	M	M	M	M	M	20
ww	170	w	Asphalt enamel	14	M	34	M	M	M	15	20	U	M	M	U	20	U	M
kk	165	k	Coal-tar–asphalt enamel	R	R	H	M	M	M	R	28	M	U	U	M	12	U	20
d	342	dd, ddd	Coal-tar enamel	M	R	R	M	R	R	M	M	M	U	U	U	M	R	U

6. SHIELDED, REINFORCED COATINGS

r	105	.....	Grease	M	M	54	14	M	M	M	20	M	R	10	R	17	M	M
yy	199	.....	Asphalt	M	18	35	14	M	M	M	25	M	M	13	U	13	11	28
qq	216	q	....do	R	M	38	M	M	M	M	15	M	M	U	U	U	U	M
yx	0.4	.....	Metal coating	22	27	2H	46	23	42	34	37	100+	39	42	65	33	15	H

[1] In mils.
[2] See table 15 for a description of the coatings.
[3] See Appendix 2 for a description of the soils.
[4] The associated coating is similar to the coating on the same line except for a change in priming coat, reinforcement or shield.
[5] Rusted—no appreciable pit depths.
[6] Pits less than 10 mils in depth.
[7] Pipe shows no corrosion.
[8] Without shield.

TABLE 78.—*Summary of conditions of 3-inch coated pipe.*

Coating				Total pipe inspected	Unaffected		Rusted		Metal attack		Pitted		Depth deepest pit (mils)
Symbol	Thickness (mils)	Associated coating	Character		Total pipe	Percent	Total pipe	Percent	Total pipe	Percent	Total pipe	Percent	
1. COLD APPLICATIONS													
ee	45	e	Cutback asphalt	15	0	0	4	26.7	6	40.0	5	33.3	104
u	47	.....	....do	15	0	6.7	3	20.0	3	20.0	8	53.3	H
l	81	.....	....do	15	1	6.7	1	6.7	6	40.0	7	46.7	108
zx	12	.....	Cutback coal tar	15	0	0	1	6.7	2	13.3	12	80.0	H
b	20	bb	....do	15	1	6.7	0	0	4	26.7	10	66.7	H
j	15	ppp	Asphalt emulsion	15	0	0	0	0	1	6.7	14	93.3	H
ppp	15	j	....do	15	0	0	1	6.7	2	13.3	12	80.0	H
fff	37	f, ff	....do	15	0	0	0	0	1	6.7	14	93.3	H
2. ENAMELS													
vv	79	.....	Asphalt	15	0	0	2	13.3	6	40.0	7	46.7	62
w	92	ww	....do	15	0	0	0	0	4	26.7	11	73.3	H
s	41	ss	Coal-tar asphalt	15	7	46.7	1	6.7	3	20.0	4	26.7	24
k	75	kk	....do	15	4	26.7	2	13.3	6	40.0	3	20.0	32
t	52	.....	Coal tar	15	0	0	1	6.7	1	6.7	13	86.7	H
dd	50	d, ddd	....do	15	1	6.7	1	6.7	4	26.7	9	60.0	154
a	54	.....	....do	15	4	26.7	1	6.7	3	20.0	7	46.7	114
g	69	zzz, g, zz	....do	14	6	42.9	2	14.2	3	21.4	3	21.4	32
z	72	.....	....do	15	7	46.7	3	20.0	1	6.7	4	26.7	H
zzz	77	p, g, zz	....do	15	7	46.7	0	0	2	13.3	6	40.0	108
p	.....	g, zz, zzz	....do	15	6	40.0	3	20.0	1	6.7	5	33.3	H
3. MASTICS													
h	69	.....	Asphalt	15	2	13.3	1	6.7	2	13.3	10	66.7	H
qqq	183	.....	....do	15	3	20.0	0	0	4	26.7	8	53.3	H
nn	337	.....	....do	15	8	53.3	3	20.0	3	20.0	1	6.7	30
v	337	.....	....do	15	10	66.7	2	13.3	3	20.0	0	0	.....

4. SHIELDED COATINGS

x	18	.....	Cutback asphalt.....	15	1	6.7	2	13.3	5	33.3	7	46.7	H
ff	190	f, fff	Asphalt emulsion.....	15	2	13.3	2	13.3	7	46.7	4	26.7	63
ss	[1] 41	s	Coal-tar-asphalt enamel...	15	11	73.3	1	6.7	2	13.3	1	6.7	21
ddd	[1] 50	d, dd	Coal-tar enamel.....	15	12	80.0	1	6.7	2	13.3	0	0	.....
zz	[1] 77	zzz, p, g	....do.....	15	12	80.0	1	6.7	2	13.3	0	0	.....

5. REINFORCED COATINGS

c	72	cc	Cutback asphalt.....	15	0	0	1	6.7	5	33.3	9	60.0	112
bb	34	b	Cutback coal tar.....	15	0	0	2	13.3	2	13.3	11	73.3	H
m	89	.....	Asphalt emulsion.....	15	0	0	0	0	9	60.0	6	40.0	90
f	149	ff, fff	....do.....	15	1	6.7	2	13.3	11	73.3	1	6.7	19
ee	22	e	Grease.....	13	0	0	0	0	4	30.8	9	69.2	H
2	26	ee	....do.....	15	0	0	1	6.7	5	33.3	9	60.0	H
y	144	yy, yyy	Asphalt.....	15	0	0	2	13.3	5	33.3	8	53.3	H
pp	138	q	....do.....	13	2	15.4	1	7.7	8	61.5	2	15.4	20
q	155	pp, qq	....do.....	15	0	0	0	0	9	60.0	6	40.0	62
n	158	.....	....do.....	15	2	13.3	1	6.7	6	40.0	6	40.0	H
yyy	259	y, yy	....do.....	15	1	6.7	0	0	10	66.7	4	26.7	29
ww	170	w	Asphalt enamel.....	15	3	20.0	0	0	6	40.0	6	40.0	34
kk	165	k	Coal-tar-asphalt enamel...	15	3	20.0	3	20.0	5	33.3	4	26.7	H
d	342	dd, ddd	Coal-tar enamel.....	15	4	26.7	5	33.3	6	40.0	0	0	.....

6. SHIELDED, REINFORCED COATINGS

r	105	.....	Grease.....	15	0	0	2	13.3	8	53.3	5	33.3	54
yy	199	y, yyy	Asphalt.....	15	1	6.7	0	0	5	33.3	9	60.0	35
qq	216	q	Asphalt.....	15	4	26.7	1	6.7	8	53.3	2	13.3	38
yx	0.4	.....	Metal coating.....	15	0	0	0	0	0	0	15	100.0	H

[1] Without shield.

(4) *Comparison of Results of Tests of Coatings Applied to Operating Lines with Those on Isolated Small Pipe.*—Table 79 was prepared for the purpose of showing the relative severity of tests of coatings applied to pipe lines and to short isolated sections of small-diameter pipe. The data are from three sources: Conductance tests, pattern tests, and measurements of pit depths. The data were derived as follows: If the results of each of the four conductance measurements made on the line coating were lower than the result of the single conductance test of the coating on the small pipe, the number of the test site for which the comparison was made was placed under the heading "lower on line." If the conductance of the coating on the small pipe was lower than any of the four coating conductances for the coating on the line, the site number was placed under the heading "higher on line." If the conductance of the coating on the small pipe was less than the conductance found by one test of the line coating and greater than that found by another test of the same coating, the site number was placed under the column headed "indeterminate." The results of the pattern tests were treated similarly. The comparison of pit depths was based on the average of the depth of the deepest pit on each of about 20 one-foot lengths of coated pipe line and the depth of the deepest pit on the small pipe similarly protected. The columns under the heading "pit depths" group the test sites with respect to whether the averages of the maximum pit depths on the line beneath the coatings were less, greater, or equal to the maximum pit depth on the corresponding small pipes.

TABLE 79.—*Comparison of results of tests of coatings applied to pipe lines and isolated sections of small-diameter pipe.*

Symbol	Thickness	Conductance test					
		Lower on line at sites	Σ	Higher on line at sites	Σ	Indeterminate at sites	Σ
1. COLD APPLICATIONS							
C	21+	VII	1	III, X	2	I, IV, V, VI, XIII	5
A	65+	IV	1		0	XIII, XIV, I, II, III, V, VI, X	8
2. ENAMELS							
N	60+	IX	1	II, VII, VIII, XI	4	III, VI	2
K	69−		0	II, III, VI, VII, XI,		V	1
M	58+	VI, XI	2	XIII, XIV	7	I, II, III, VII	4
L	80−	VII	1	X, XIV	2	III, VI	2
				II, VIII, IX, X, XI, XVI	6		
3. MASTIC							
O	519+	II, III, IV	3		0	I, V, VII, VIII, IX, XI, XIII, XVI	8
4. SHIELDED COATINGS							
Y	29+		0	VI, VIII, IX, X, XIII	5	I, IV	2
F	419+	IX, X, XIII	3	I, VI	2	V, VIII, XIII, XIV, XVI	5
G	63+	VII, X	2	III, VIII, XIII, XVI	4	II, V, VI, IX	4
H	81+	V, IX, XIV	3	III, IV, VI, VIII, XIII	5	X	1

TABLE 79.—*Comparison of results of tests of coatings applied to pipe lines and isolated sections of small-diameter pipe*—Continued.

Symbol	Thickness	Conductance test: Lower on line at sites	Σ	Higher on line at sites	Σ	Interminate at sites	Σ
		5. REINFORCED COATINGS					
B	107+	VII, XI	2	II, V, X	3	I, IV, VI, IX, XIV	5
S	150+	IV	1	I, XIV	2	II, VII, VIII, XIII, V	5
E	151−	V, XIV, XVI	3	VI, X	2	I, II, XI, XIII, IV	5
Z	201+	III, IV, IX, XI, XVI	5	I, II, V, VIII	4	VII, XIII	2
R	143−	III	1	II, VIII, IX, XI, XIV	5	IV, V, VII	3
U	171+	III, IX, XIII, XIV, XVI	5	I	1	II, IV, VII, VIII, XI	5
T	351+	XIII, VII	2	IV, VI, X, XI, XVI	5	I, VIII, IX	3
		6. SHIELDED, REINFORCED COATINGS					
X	230+	I, IV, V, XIV	4	IX, XVI	2	II, VIII, III, XI, XIII	5
Σ	.....	.....	39	.....	61	.....	75

Symbol	Thickness	Pattern test: Better on line at sites	Σ	Worse on line at sites	Σ	Indeterminate at sites	Σ
		1. COLD APPLICATIONS					
C	21+	.....	0	.....	0	I, III, IV, V, VI, VII, X, XIII	8
A	65+	.....	0	.....	0	I, II, III, IV, V, VI, X, XIII, XIV	9
		2. ENAMELS					
N	60+	.....	0	II	1	III, VI, VII, VIII, IX, XI	6
K	69−	.....	0	II, III, XI, VI, VII, XIII, XIV	7	V	1
M	58+	.....	0	.....	0	I, II, III, VI, VII, X, XI, XIV	8
L	80−	IX, X	2	.....	0	II, III, VI, VII, VIII, IX, XVI	7
		3. MASTIC					
O	519+	II, XIII, IX.	3	IV, VII.	2	I, III, V, VIII, XI, XVI	6
		4. SHIELDED COATINGS					
G	63+	.....	0	II, III, IX, XVI, VIII, XIII	6	VI, V, X, VII	4
H	81+	.....	0	III, IV, V, VIII, X, XIV	6	IX, VI, XIII	3
		5. REINFORCED COATINGS					
B	107+	.....	0	X, XI	2	I, II, IV, V, VI, VII, IX, XIV	8
S	150+	.....	0	X, XIV	2	I, II, IV, VII, VIII, XIII	6
E	151−	.....	0	I, II, X, XIV	4	IV, VI, XI, XIII, XVI	5
Z	201+	.....	0	I, IV, V, VII	4	II, III, VIII, IX, XI, XIII, XVI	7
R	143−	.....	0	I, II, IV, V, VII, IX, XI, XIV	8	III, VII, VIII, IX	4
U	171+	.....	0	I, IV, VII, XIV	4	II, III, XI, VIII, XIII, XVI, IX	7
T	351+	.....	0	IV, IX, X, XI, XVI	5	I, VI, VII, VIII	4
		6. SHIELDED, REINFORCED COATINGS					
Σ	.....	.....	5	.....	48	.....	93

TABLE 79.—*Comparison of results of tests of coatings applied to pipe lines and isolated sections of small-diameter pipe*—Continued.

Symbol	Thickness	Pit depths					
		Shallower on line at sites	Σ	Deeper on line at sites	Σ	Equal at sites	Σ
		1. COLD APPLICATIONS					
C	21+	VI, VII	2	I, IV, V, XIII	4	III, X	2
A	65+	IV, XIII	2	I, II, V, VI, X, XIV	6	III	1
		2. ENAMELS					
N	60+	IX	1	II, III, VI, VII, VIII, X, XI	7		0
K	69−		0	II, III, V, VI, VII, X, XI, XIII, XIV	9		0
M	58+	VII, XIV	2	I, II, VI, X, XI	5	III	1
L	80−		0	II, III, VI, VII, VIII, IX, X, XI, XVI	9		0
		3. MASTIC					
O	519+	III, IX	2	I, II, IV, V, VII, VIII, XI, XVI	8	XIII	1
		4. SHIELDED COATINGS					
Y	29+		0	I, IV, VI, VIII, X, XIII, XIV, IX	8		0
F	419+	IX	1	I, V, VI, VIII, X, XIII, XIV, XVI	8		0
G	63+		0	II, III, V, VI, VII, VIII, IX, X, XIII, XVI	10		0
H	81+		0	III, IV, V, VI, VIII, IX, X, XIII, XIV	9		0
		5. REINFORCED COATINGS					
B	107+	XIV	1	I, II, IV, V, VI, VII, IX, X, XI	9		0
S	150+	XIII	1	I, II, IV, V, VII, VIII, XIV	7		0
E	151+	I, IV, XIII	3	II, V, VI, X, XI, XIV, XVI	7		0
Z	201+	III	1	I, II, IV, V, VII, VIII, IX, XI, XVI	9	XIII	1
R	143−	I, III	2	II, IV, V, VII, VIII, XI, XIV	7	IX	1
U	171+	IV, IX, XIV, III	4	I, II, VII, VIII, XI, XIII	6	XVI	1
T	351+		0	I, IV, VI, VII, VIII, IX, X, XI, XVI	9		0
		6. SHIELDED, REINFORCED COATINGS					
X	230+	III, VIII, IX, IV	4	I, II, V, XI, XIII, XIV, XVI	8		0
Σ			26		145		8

The results of the two methods of testing coatings, that is, on operating pipe lines and on isolated sections of small pipe, are not strictly comparable for several reasons.

1. The thickness of the coating on the line and on the corresponding small pipe was not always identical, as is shown in the second column of table 79, in which a plus sign is placed after the thickness of the coatings that were thicker on the pipe line and a minus sign after the thicknesses of coatings that were thinner on the pipe line.

2. The results of four or more observations are compared with the

result of a single observation, the reproducibility of which cannot be determined.

3. The tests were all based on some measurement of a worst condition, and on such a basis, the tests are more severe with respect to the coatings on the line, because these coatings had greater areas from which the worst condition was selected. This statement holds for the conductance tests, although the results were expressed as conductance of 1 square foot of coating, as the conductance was not uniform but was largely controlled by the conductance of some small, defective area. In the case of the pit depth comparisons, the area of 1 linear foot of line pipe ranged between 201 and 338 square inches, whereas the area beneath the coating on the small pipe was about 140 square inches.

Each of the tests, therefore, would have a tendency to make the coating applied to the line appear to be in the worst condition even if the actual conditions on a unit-area coating on the two sizes of pipe were identical.

This is but another way of saying that if the coating is judged by the worst condition found on that coating, the severity of the test increases with the area of the coating exposed to the test. This may be a sufficient explanation of the fact that table 79 indicates that, on the whole, the conditions of the coatings on the pipe line were worse than the conditions of the coatings on the small sections of pipe. This explanation is supported by the large number of cases in which the result of a test of a coating on a small pipe fell between the results of the four tests of the corresponding coating on the operating line.

Table 79 shows that in many cases the coating on the small pipe was in a worse condition than the corresponding coating on the operating line. This condition is not confined to any one soil or coating, and there seems to be no correlation between the relative merits of the coatings in the two tests and either the character of the soil or the nature of the coating. Probably many of the apparent differences in the conditions of the same coating under the two types of test are the results of variations in the conditions of the soil or coating or of other accidental variations. This is suggested by the fact that in both the conductance and pattern tests a large percentage of the results falls in the indeterminate classification.

Although table 79 indicates that, in the majority of cases, the coatings applied to the pipe line deteriorated more than the corresponding coatings applied to small-diameter pipe, the fact that the conditions of the two tests were not identical prevents the conclusion that table 79 shows that a test of the coatings on the line is necessarily more severe than the other test if the exposed areas of the coatings are the same.

A question of equal importance is whether or not the two tests place coatings in the same relative positions. Inasmuch as the plans for the tests specified that the names of the makers of the line coatings should not be revealed, the publication of a table comparing the results given in tables 75 and 78 is not permissible. However, such a table has been prepared for the purpose of answering the question just mentioned. It will be seen that tables 75 and 78 permit the arrangement of the coatings in order of merit on three bases: (1) percentage of unaffected pipe, (2) percentage of coatings that permitted the formation of pits, and (3) the depth of the deepest pits beneath each coating.

When coatings were arranged in order of merit as indicated by the percentage of protected pipe unaffected, percentage pitted, and the

maximum pit depth for the two kinds of exposures, it was found that the three bases for comparison did not arrange the coatings in exactly the same order. The average range in rank for the line coatings in the three tests was approximately 5.4 positions, whereas the average range for the same coatings on the small pipe was about 3.6 positions. Table 80 shows comparisons of the ranks of coatings on pipe lines and isolated pipes grouped according to their structures. The comparisons are based on three criteria of the condition of the pipe beneath the coating, as shown in tables 75 and 78. Table 80 may indicate that the line tests of the unreinforced coatings, which in this table included cold applications, enamels, and a mastic, were on the whole somewhat more severe than the tests of these coatings on the isolated pipe, but the indications are not very definite. The grand totals of the results show that, although two ways of testing coatings yield different results with respect to ranking individual coatings, neither method greatly favors any class of coatings. It seems probable that the differences in ranking by the two test methods are not greater than the variations in ranking resulting from the lack of control of the test conditions.

TABLE 80.—*Comparison of the ranking of coatings on pipe lines and isolated pipe.*

Test criterion	Number of line and isolated coatings having same rank			Number of line coatings ranked higher (better)			Number of line coatings ranked lower (worse)		
	Unreinforced	Reinforced	Shielded	Unreinforced	Reinforced	Shielded	Unreinforced	Reinforced	Shielded
Percent unaffected	1	5	1	1	2	1	5	0	3
Percent pitted	3	1	1	1	4	3	3	2	1
Deepest pit	1	3	.....	2	2	3	4	2	2
Total	5	9	2	4	8	7	12	4	6
Grand total	.....	.....	16	.....	.....	19	.....	.....	22

As the tests were conducted, the conditions were apparently more severe for the coatings on the line, and the results of the tests of coatings on the pipe lines were more dependable because of the greater number of observations for each coating. But these facts do not indicate that tests of coatings by applying them to working lines are better than tests of coatings on isolated sections of pipe for determining the relative merits of coatings if the same amount of data is obtained by each test.

(5) *Effect of Time on Rate of Corrosion of Coated Pipe.*—It should be evident from the data presented that the production of even a few feet of coating that would remain continuous for as long as 10 years was a difficult undertaking. Data on more recent coating installations indicate that the problem is still difficult. Nevertheless, complete protection of the pipe is the goal sought. A combination of a protective coating with cathodic protection might be more economical and more effective than an attempt to maintain a continuous coating. The current required for cathodic protection will be determined to a considerable extent by the conductivity of the coating. For this reason, rather than as a means of indicating the effectiveness of the coatings, table 81 is reproduced from the final report on the API tests [61].

It should be pointed out that the conductivity of the coating as reported depends largely on the conductance of the solution in the pores and other openings, which in turn depends on the number and size of the openings, the thickness of the coating, and the conductivity of the soil solution in the openings. The data are also affected to some extent by the way in which the measurements were made. Those readers who are accustomed to think in terms of resistance rather than conductance can reduce the conductances to resistances by dividing the latter into 10^6. It will be seen that some of the coatings are much poorer conductors than others.

It has been shown that in aerated soils the rate of penetration of bare iron and steel pipe decreases as the period of exposure increases. It is of interest to inquire whether the penetration of coated pipe is similar. The API tests do not answer the question positively but throw some light on it.

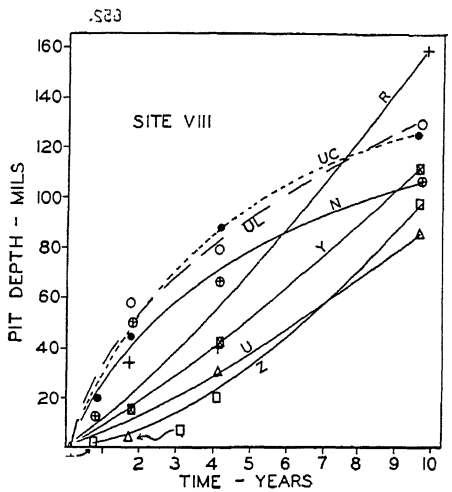

FIGURE 40.—*Relation of pit depths on coated pipe to duration of exposure.*

UC, unprotected control pipe; *UL*, unprotected line pipe; *R*, asbestos-felt–reinforced asphalt enamel; *N*, coal-tar enamel; *U*, asbestos-felt–reinforced coal-tar enamel; *Y*, aluminum-foil–shielded asphalt cut-back; *Z*, asphalt reinforced by two layers of asphalt-saturated cotton fabric. See appendix 2 for description of the test sites.

Because of the effectiveness of some of the coatings, the mild corrosiveness of the soil of some of the test sites, and the lack of uniformity in some of the soils and coatings, many of the sets of observations did not yield data that definitely indicated the relation of pit depths to time. However, 9 of the API test sites yielded fairly satisfactory data for 3 or more coatings, and these data have been plotted in 12 sets of curves [77], one of which is shown in figure 40. In these figures, pit-depth–time curves were shown for pipe protected by 17 types of bituminous coatings, which were representative of most of the coatings in use when the API tests were started in 1930. Each point on the curves for protected pipe represents the average of the depths of the deepest pit on each of two 5-foot sections of coated pipe in an operating pipe line, usually a line of 8 inches in diameter. The points on the curve for the uncoated pipe line, UL, figure 40, are based on averages of the deepest pit on each of twelve 4-foot sections of uncoated pipe line. The points on the curve for the control pipe, UC, are based on the averages of the

TABLE 81.—*Maximum conductance*[1] *of coatings on operating pipe lines.*

Coating [2]					Test sites [3]													
Symbol	Thickness (mils)	Associated coating	Character	Section	I. Temple, Tex.	II. Arkansas City, Kans.	III. Beaumont, Tex.	IV. League City, Tex.	V. Preble, Ind.	VI. Council Hill, Okla.	VII. Caney, Kans.	VIII. Spindle Top Gully, Tex.	IX. Long Beach, Calif.	X. Mt. Auburn, Ill.	XI. Skiatook, Okla.	XIII. Bunkie, La.	XIV. Chambersburg, Pa.	XVI. Cholame Flats, Calif.
1. COLD APPLICATIONS: CUTBACK C; EMULSION A																		
C	21	Y	Cutback coal tar	a	2,510	.....	[4] E	2,700	E	E	4,800	.....	.....	E	.....	E	.....	.....
				b	E	.....	E	1,600	E	4,300	3,200	.....	.....	E	.....	E	.....	.....
A	65	F	Asphalt emulsion	a	E	E	E	4,000	E	930	.....	.....	.....	E	.....	E	.....	.....
				b	E	E	E	4,800	E	E	.....	.....	.....	270	.....	12,000	570	.....
2. ENAMELS																		
N	60	G	Coal-tar–asphalt enamel	a	.....	3.5	138	.....	.....	E	240	E	23	D	4,700	.....	.....	.....
				b	.....	98	E	.....	.....	24	1,600	E	98	.....	1,400	.....	.....	.....
K	69	U	....do	a	.....	E	124	.....	E	270	120	.....	.....	E	3,500	E	E	.....
				b	.....	E	E	.....	67	E	E	.....	.....	0.25	1,000	E	130	.....
M	58	.....	Coal-tar enamel	a	E	E	E	.....	.....	28	E	.....	.....	E	17,000	.....	.....	.....
				b	[5] D	E	E	.....	.....	1,200	E	.....	.....	E	10,000	.....	E	.....
L	80	H	....do	a	.....	580	576	.....	.....	E	1,100	E	8,700	66	4,700	.....	.....	.....
				b	.....	E	E	.....	.....	E	18	E	51	440	3,400	.....	.....	22,000
3. MASTIC																		
O	519	.....	Asphalt mastic	a	5.4	10	11	12	13	.....	30	55	0.23	.....	32	13	.....	330
				b	110	16	2	21	12	.....	8	620	52	.....	290	8.9		87

4. SHIELDED COATINGS: CUTBACK Y; EMULSION F; AND ENAMELS

Y	29	C	Cutback asphalt.....	a	E	.....	.....	8,900	.....	E	.....	E	E	E	.....	E	D	.....
				b	E	.....	.....	31,000	.....	27,000	.....	E	E	E	.....	13,300	D	.....
F	419	A	Asphalt emulsion.....	a	220	.....	.....	.....	1,200	3,600	.....	E	810	1,700	.....	1,200	1,200	E
				b	720	.....	.....	.....	2,800	650	.....	3,100	1,300	2,000	.....	800	750	1,600
G	63	N	Coal-tar-asphalt enamel	a	.....	4.5	200	.....	0.08	2.3	0.005	190	60	8.9	.....	360	.....	E
				b	.....	98	29	.....	9.0	470	0.004	260	460	D	.....	1,900	.....	E
H	81	L	Coal-tar enamel.....	a	.....	.....	800	1,800	0.15	E	.....	E	0.87	0.016	.....	E	12	.....
				b	.....	.....	220	2,300	0.001	330	.....	E	1.9	4.6	.....	E	0.00	.....

5. REINFORCED COATINGS

B	107	.....	Grease.....	a	E	670	.....	E	E	E	36	.....	2,800	E	D	.....	E	.....
				b	E	710	.....	E	110	12	110	.....	38,000	E	2,700	.....	D	.....
S	150	.....	Asphalt.....	a	E	530	.....	D	71	.....	33	E	.....	.....	.....	E	380	.....
				b	E	E	.....	250	230	.....	E	1,700	.....	.....	.....	1,400	.....	.....
E	151	.....	....do.....	a	360	150	.....	240	75	E	.....	.....	.....	E	6,800	17,000	50	18,000
				b	D	240	.....	620	55	E	.....	.....	.....	E	5,500	5,800	11	1,300
Z	201	X	....do.....	a	220	E	800	51	E	.....	440	E	620	.....	3,500	2,900	.....	440
				b	E	E	580	14	E	.....	E	E	2,300	.....	2,200	E	.....	1,100
R	143	.....	Asphalt enamel.....	a	E	2,000	1,300	1,300	570	.....	16	E	12	.....	1,300	.....	67	.....
				b	E	E	130	440	38	.....	2,400	E	20	.....	2,000	.....	E	.....
U	171	K	Coal-tar-asphalt enamel	a	650	29	80	14	.....	.....	220	2,500	.....	.....	6,600	360	0.24	220
				b	320	67	31	1,200	.....	.....	2,100	E	17	.....	1,600	800	0.64	360
T	351	.....	Coal-tar enamel.....	a	90	.....	.....	190	.....	150	120	310	45	110	810	.....	.....	2,000
				b	510	.....	.....	160	.....	190	130	620	170	.....	120	.....	.....	180

6. SHIELDED, REINFORCED ASPHALT

X	230	Z	Asphalt.....	a	13	40	E	11	7.1	.....	.....	530	10,000	.....	680	530	6.9	E
				b	3.6	210	580	42	20	.....	.....	14,000	5,200	.....	68	4,000	32	.....

[1] In micro-mhos per square foot.
[2] A description of these coatings is given in table 16.
[3] The coating in column 1 and the related coating in column 3 contain, with the exception of coatings C and Y, the same bituminous material.
[4] E = pipe exposed.
[5] Coating damaged by tools.

deepest pit on 24 individual 18-inch lengths of pipe. In addition to the tests of coatings applied to pipe lines, the API tests included 46 varieties of coating applied to 2-foot lengths of boiler tube. These specimens were placed in a trench near the pipe line at each site. Only three specimens of each material were provided for each test site. The heavily coated specimens showed no pits at the first inspection. The lightly coated specimens in the corrosive soils were punctured at the close of the test. On this account, these specimens yielded few data from which pit-depth–time curves could be plotted.

Figure 41 shows the data for one test site. The curves are similar to those for the coated line pipe. Incidentally, it is of interest to compare the curves for the uncoated boiler tube, UB, buried with the coatings with that of the uncoated control pipe, UC, buried next to the pipe line

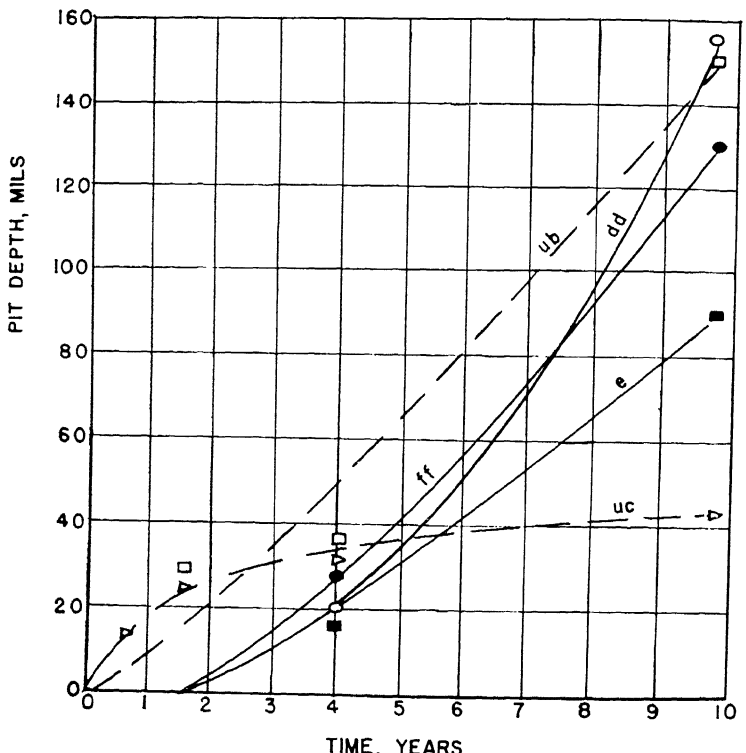

FIGURE 41.—*Pit-depth–time curves for coatings applied to boiler tube at American Petroleum Institute site, XIII.—Miller clay.*

dd, Coal-tar enamel; *e*, cotton fabric reinforced, chromated grease; *ff*, asphalt-chromate emulsion; *ub*, uncoated boiler tube; *uc*, uncoated control pipe in adjacent trench with pipe line.

a few feet distant. During the first 4 years the two pitted at approximately the same rate but at the end of the 10 years of exposure, three of the four boiler tubes were punctured, whereas the control pipes showed little increase in pit depths. At this site the pitting on the line was much deeper than on the control pipes.

Most of the pit-depth–time curves for the coated pipes do not bend toward the abscissa as much as do the corresponding curves for the unprotected pipe. In a number of cases, the curves indicate that the

rate of pitting did not decrease as the exposures lengthened and in several cases there appears to have been a slight acceleration of the rate of pitting. If these curves truly represent the course of corrosion of coated pipe, in the long run many of the pipes that were coated would be punctured before the adjacent uncoated pipe. There are a considerable number of cases in which at the 10-year period of inspection the pits on the coated pipe were deeper than those on the uncoated pipe, and at two sites the pipe beneath one or more of the coatings was punctured.

The general dissimilarity between pit-depth–time curves for bare and coated pipe exposed to the same soil conditions cannot be accounted for by characteristics of the coatings or of the soils to which the coatings were exposed, because widely different coatings yielded similar curves, and the curves are similar for widely different soils. The curves for a pipe protected by a specific coating may or may not be similar in different soils, and the factor that determines the shape of the pit-depth–time curve is not apparent from the available data.

The results that have been presented may represent the normal behavior of pipe protected by coatings or abnormal conditions arising from the way in which the tests were conducted or the way in which the data were treated. The alternation of coated and bare sections of pipe may have set up conditions of differential aeration that intensified the corrosion beneath the coatings and these conditions may have been aggravated by the exposure of additional pipe and the increased aeration of the soil at each period of inspection. In considering this suggestion, one should remember that it is the shape of the curves, that is, the change in curvature with time, and not the magnitude of the pit depths that is the topic to be considered. Comparisons of pit depths on the uncoated line pipe with those on the uncoated control pipe do not definitely indicate that the unprotected line pipe received cathodic protection at the expense of the coated pipe because of differential aeration.

It is possible, however, that the effect of the bare sections on the coated sections of pipe is obscured by other phenomena and cannot be shown by a comparison of the bare sections of the line with the bare control pipe because of differences in area, soil pressure, curvature of pipe, or other conditions. Unless the bare sections of pipe tended to maintain the rate of penetration of the coated pipe and to make the pits deeper, the effect of the bare sections is of little importance with respect to the curves. It is much easier to show that because of differential aeration the bare sections may have caused an increase in the depths of the pits on the coated sections than to explain how the bare sections caused the rate of penetration of the coated sections to be maintained. As the coatings became older, the effect of differential aeration probably decreased because of the increased number of holes in the coating and the greater compactness of the soil around the unprotected pipe. The results of the tests of the coatings applied to isolated sections of pipe parallel those for the coatings applied to the pipe lines and lead to the same conclusions as to the relation between pit depths and the age of the coatings. This indicates that the presence of the bare sections of the pipe did not exert a controlling effect on the pit-depth–time curves for the curves for the coated line pipe.

The difference in the shapes of the pit-depth–time curves for coated and uncoated pipe could be explained in part at least by the assumption that the pits beneath the coating did not start until some time after the tests began. Correction of the ages of the pits for this lag in time of

start would yield curves showing higher initial rates of penetration and, consequently, greater bending toward the time axis. There is no way of determining when the pits started, and therefore it is impossible to evaluate the importance of this explanation.

The two explanations that have been outlined above attribute the shapes of the pit-depth–time curves for coated pipes to conditions associated with the test rather than with the characteristics of the coatings tested. A second class of explanation implies that the results of the tests reveal tendencies which are to be expected whenever a coated pipe corrodes under certain normal conditions. In the case of coatings containing organic materials that decay, conditions may be more favorable for the development of certain bacteria to which corrosion under certain environmental conditions has recently been attributed [78, 79]. A pipe line frequently picks up and discharges currents commonly designated as long line currents, and an imperfect coating may increase the current density of these currents at points where the coating has failed.

The theory of differential aeration as a cause of corrosion, which was mentioned in the discussion of the effect of the unprotected sections of the line, may also be used to explain why sustained rates of corrosion of coated pipes are to be expected. Rates of underground corrosion depend on two factors: the tendency of the metal to go into solution, indicated by the potential of the corroding metal with respect to the electrolyte, and the corrosion-repressing power of the corrosion products including those frequently termed polarization films. Both of these factors are influenced by the amount and distribution of the oxygen in the soil. It has been shown [56] that the poorer the aeration of the soil the more nearly constant is the rate of corrosion. It is reasonable to suppose that the coating reduces the accessibility of oxygen to the pipe and hence tends to maintain a more nearly uniform rate of pitting than on unprotected pipe. This seems to the writer to be the most reasonable explanation of the sustained rates of corrosion shown by many of the pit-depth–time curves.

Since the pit-depth–time curves in figures 41 and 42 represent only selected data and are free-hand curves arbitrarily drawn, it is desirable to eliminate the personal equation involved and to examine all of the pit-depth data for the longest period of exposure to see whether they point to a similar conclusion. Several basically different comparisons of pit-depths on coated and uncoated pipe can be made, although each comparison has some objectionable feature.

The comparison that will be presented first is based on the data from which the curves were plotted. The final report [61] on the API coating tests shows 30 cases out of a possible 175, or about 17 percent, in which the average of the depth of the deepest pit on each of two 5-foot sections of coated pipe was deeper than the average of the depths of the deepest pit on each of twelve 4-foot sections of unprotected pipe at the same site. The 30 cases comprise 12 coatings and 10 test sites. If the single deepest pit on a section of pipe is made the basis of comparison, there are 67 cases out of a possible 334 cases, or 20 percent, in which the deepest pit on a 5-foot section of the coated pipe was deeper than the deepest pit on the 4-foot section of uncoated pipe nearest to the coated section. The 67 cases comprise 14 coatings and 12 sites.

Maximum pit depths are to some extent the results of additive combinations of circumstances and are therefore less significant than averages, as the latter tend to minimize these cumulative circumstances. There are 16 cases out of a possible 169, or 9 percent, in which the av-

erage of the depths of the deepest pit on each of approximately twenty 1-foot sections of the coated pipe was greater than the average of the depths of the deepest pit on each of about sixteen 1-foot sections of unprotected pipe adjacent to the coated pipe. The 16 cases comprise 7 coatings and 8 soils, and when compared with the data previously given, illustrate the effect of basing comparisons on averages instead of maximum figures.

As the pitting of the bare sections of the line may have been influenced by the alternation of coated and uncoated sections, a comparison will next be made of the pit depths on the coated line with those on the adjacent lengths of isolated control pipe. There were 10 cases out of a possible 156, or 6 percent, in which the average of the deepest pit on each foot of pipe beneath a coating was greater than the average of the deepest pit on each of two 36-inch lengths of control pipe adjacent to the coating. The 10 cases involve 7 coatings and 4 soils.

The relative slope of the pit-depth–time curves for coated and uncoated pipe is more important than the relative depths of the pits at the close of the 10-year period of exposure. There are 83 cases in which measurable pits were found beneath coatings on the operating lines at both the third and the fourth inspection. If the maximum pit depth on the 5-foot coated section is divided by the average of the depth of the deepest pit on 4 feet of each uncoated section of pipe at the same site, there are 52 cases out of the possible 83 in which the quotient is greater for the last period of inspection than for the preceding one. In other words, in about 53 percent of the cases the rate of pitting beneath the coatings decreased more slowly than the rate of pitting of the uncoated pipe. This comparison is too favorable to the coatings because it does not take into account 52 sections of coatings that prevented pitting during the first four years of exposure but permitted pits to develop during the subsequent 6 years.

The comparisons of pit depths on coated and uncoated line pipe tend to confirm the indications of the pit-depth–time curves. As the data for the pit-depth comparisons were derived from the same source as those for the pit-depth–time curves, these comparisons show only that the curves have been plotted correctly. Because the data presented above may have been affected by the interaction of the coated and uncoated sections of the line, the data on the short sections of isolated pipe are of interest, although, for reasons already explained, there are not many of these data.

If all the coated pipe that developed measurable pits during both the 4-year and 10-year periods of exposure are considered, there are 18 cases out of a possible 107 in which the rate of penetration was higher for the longer period of exposure. In other words, about 17 percent of the specimens to which coatings had been applied showed an increasing rate of pitting. There were 35 cases out of a possible 67 in which the quotient obtained by dividing the maximum pit depth on the coated pipe by the average maximum pit depth on the uncoated pipes at the same site was greater for the 10-year period of exposure than for the 4-year period. This is equivalent to saying that for 52 percent of the pipe protected by coatings, the maximum rate of penetration decreased more slowly than on bare pipe at the same site. This comparison is somewhat too favorable to the coatings, as no account has been taken of the pipe protected by coatings that were punctured at the close of the 10-year period or of the cases where the coated pipe showed no measurable pits at the end of the 4-year period, but did show measurable pits at the end of the

longer period of exposure. In a general way at least, the data for the coatings on the line are in agreement with those for the coatings on the isolated pipe. Although it is possible that the cases which indicate that the coatings accelerated the corrosion are accidental, the percentage of such cases makes this seem doubtful. The implication of the data that have been presented raises a serious question as to the ultimate usefulness of coatings which are imperfectly applied, contain pinholes, or allow the pipe to become exposed because of pipe movements, soil stress, penetration by roots, or deterioration of the coating materials.

The available data are insufficient to justify positive and final conclusions as to the explanations for the shapes of the curves that have been presented or as to their significance. Nevertheless, the data are sufficient to warrant very thoughtful consideration, as they may contain an explanation for much of the pipe-line trouble that has been experienced.

The reader should of course keep clearly in mind the fact that even an accelerated rate of pitting on coated pipes which are not completely protected does not imply that the coating will not prolong the useful life of the pipe, as occasional leaks may be repaired at no great cost. The summary of the data in the final report [61] indicates quite clearly that even the least effective coating reduced the number of feet of pitted pipe and that less than 2 percent of the footage of the pipe with the most effective coating showed any pits. The reduction in the total number and average depth of pits on the coated pipe was much greater than is shown by the table referred to.

The solution of the problem of pipe-line protection seems to be better coatings supplemented by cathodic protection to take care of the imperfections that are not avoided by better materials and better application.

(6) *Conclusions based on the API Tests.*—The data on the conductance of the coatings lack uniformity. Not infrequently one section of a coating showed many times the conductance of another section of the same coating at the same test site. In many cases it is difficult or impossible to determine whether this lack of consistency is the result of lack of uniformity in the thickness or composition of the coating, poor application, or of nonuniform soil conditions. The same statements are applicable to maximum pit depths. The important fact is that the amount of protection afforded by many coatings was not uniform even under nominally the same condition. Either the coatings as applied were not uniform or they lacked a sufficient factor of safety to provide against the variations in the exposure to which they were subjected.

There was a general increase in the conductance of the coatings over that observed in 1934. This indicates that the usefulness of the coatings is limited with respect to time. There are individual exceptions to this generalization.

As a class, the coatings that were applied cold and were not reinforced or shielded showed more cases of exposed pipe than did the thicker coatings.

Zinc chromate and baked-on red and blue lead appear to be satisfactory as undercoats under the conditions to which they were subjected. The bond between the undercoats and the pipe was stronger than that between the undercoats and the coatings applied over them. These undercoats seem to have reduced corrosion, but did not afford adequate protection to pipe in corrosive soils.

The number of coated pipe showing patterns was greater in 1940 than in 1934, although some sections that showed a positive pattern in

1934 showed none in 1940. The pattern tests indicate a continued decrease in the effectiveness of most coatings.

Only four test sites were severely corrosive, as indicated by the depths of the pits on unprotected sections of pipe. The majority of the test sites were, therefore, favorable to the coatings, if pit depths are used as criteria for the effectiveness of the coatings. There is no consistent difference between the depths of the deepest pits on uncoated sections of line pipe and on the uncoated short pipe sections.

On the average, the pipe under more of the coatings showed corrosion in 1940 than in 1934, and the maximum pit depths were greater for most coated sections.

In general, there were fewer pits under thick coatings than under thin ones, but the depths of the pits under a thick coating were sometimes greater than under a thinner one.

Because the coatings differ in many ways, it is impossible to determine positively whether the machine-applied coatings were superior to those applied by hand or to determine the relative merits of coal tar and asphalt as protective coatings. Likewise, the data do not show clearly whether impregnated asbestos felt was superior to organic materials as a reinforcement. However, as a shield it did not deteriorate as did the organic materials. A layer of cement-sand mortar over an emulsion coating was insufficient to prevent serious pitting in a corrosive soil.

All the coatings reduced the number of pits per unit area of surface, and most of the coated sections of pipe showed shallower maximum pit depths than occurred on the corresponding unprotected pipe. Several of the coatings afforded nearly complete protection to most of the sections of pipe to which they were applied, but no coating completely protected all sections.

The primary purpose of the test was to establish engineering principles related to the manufacture and use of protective coatings for pipe lines. The following are some of the facts established by the test.

1. Many of these coatings will greatly reduce corrosion during at least 10 years (the period of this test), although complete protection from all corrosion has not been realized in corrosive and destructive soils.
2. The effectiveness of all coatings tested decreased throughout the period of the test. This in most cases is the result of continued soil pressure and the absorption of water. There appears to be little change in the coating materials other than that in the organic fabrics used as reinforcements or shields.
3. Shields and reinforcements should be permanent and sufficiently rigid to distribute soil stress and pressure due to the weight of the pipe over enough area to prevent the flow of the bituminous or other material used in the coating.
4. Thickness of material is an important factor in coating construction.
5. A coating should be sufficiently rigid to withstand pressures over long periods and elastic enough to withstand stresses resulting from pipe movement and sudden changes in temperature. These requirements are difficult to reconcile.
6. Under certain conditions, a coating that fails to protect at a few points may cause deeper pits than would have occurred on uncoated pipe in the same location.
7. Many soils are only mildly corrosive, and no protective coating is required in them unless the cost of a leak would be abnormally high.
8. The economics of the general problem should be considered.

3. NONBITUMINOUS, NONMETALLIC COATINGS

Among the corrosion-resistant materials buried by the National Bureau of Standards in 1932, and subsequently, were a number of specimens of newly developed nonbituminous, nonmetallic coatings, some of which had been applied to short sections of pipe lines. Others have not yet been sufficiently developed to justify such trials. The Bureau's tests should be regarded as preliminary or elimination tests, as they are subject to the limitations already discussed. It is possible that, at present, some of the coatings under observation are too expensive for general use. In a number of cases the problems of field repairs that are unavoidable and the application of the coatings to joints in the line and to fittings have not been solved. Nevertheless, the results of the tests are of interest and suggest new ways of attacking the pipe-protection problem. The coatings are described in table 12.

(a) AFTER 9 YEARS OF EXPOSURE

Table 82 shows the condition of the pipe beneath the coatings exposed for 9 years. It will be noted that the two thick rubber coatings completely protected the pipes except at the ends where moisture got be-

TABLE 82.—*Condition beneath nonmetallic coatings exposed for 9 years.*

[Figures indicate depths of maximum pits in mils]

E, ends corroded.
G, ends rusted.
H, pipe punctured, 145+ mils.
M, metal attack—pipe roughened by corrosion.
R, pipe rusted.
P, definite pitting but no pits greater than 6 mils.
U, no corrosion.
D, pipe destroyed by corrosion.

Soil		Specimen No.	Porcelain enamel	Rubber paint	Paint	Cashew-nut-oil-asbestos fiber	Hard rubber	Loaded hard rubber	Synthetic resin	Chlorinated rubber paint	China wood-oil mica compound	Uncoated low-carbon-steel pipe
No.	Type		C	D	E	F	G	H	J	K	W	N
53..	Cecil clay loam	1	U	M	17	M	....	....	M	16	M	59
		2	UE	9	15	R	....	....	M	24	M	59
		3	....	....	....	....	....	....	....	27	....	....
55..	Hagerstown loam	1	R	M	16	R	....	....	....	....	M	48
		2	U	M	28	R	....	....	....	....	M	70
56..	Lake Charles clay	1	UE	[a] 51	[b] H(7)	M	....	....	....	....	M	H(154+) (7)
		2	ME	[a] 38	[a] 104	M	....	....	....	....	M	H(154+)
58..	Muck	1	54E	53	97	61	....	....	....	....	M	[a] 122
		2	R	52	H(7)	R	....	....	....	....	R	[a] 98
59..	Carlisle muck	1	U	19	P	M	U	U	....	....	M	25
		2	U	M	15	R	U	U	....	....	M	54
60..	Rifle peat	1	U	15	[a] 38	31	U	U	....	....	M	18
		2	UE	[a] 44	[a] 25	R	U	U	....	....	M	[a] 36
61..	Sharkey clay	1	U	R	58	R	....	....	....	....	M	130
		2	U	U	48	R	....	....	....	....	MG	62
62..	Susquehanna clay	1	U	U	27	R	....	....	....	....	MG	121
		2	U	23	25	27	....	....	....	....	M	53
63..	Tidal marsh	1	UE	M	....	P	....	....	....	....	....	44
		2	....	....	....	....	....	....	....	....	....	65
64..	Docas clay	1	RE	37	D(7)	M	UE	M	[a] 122	52	M	H(154+) (5, 7)
		2	UE	47	D	M	UG	U	[a] 125	60	R	H(154+)
65..	Chino silt loam	1	U	12	D(7)	P	UE	U	....	....	MG	118
		2	U	11	[a] 87	R	UG	U	....	....	M	106
66..	Mohave fine gravelly loam	1	UE	29	[a] 77	34	UE	U	....	....	M	H(154+) (5, 7)
		2	U	15	[a] 122	M	UE	UE	....	....	M	H(154+)
67..	Cinders	1	UE	77	D(7)	16	UE	UE	H(7)	[a] 92	R	H(154+) (2, 5, 7)
		2	43E	H	H	R	UE	UG	H	....	ME	H(154+)

[a] Severe uniform corrosion; no reference surface; impossible to measure true penetration.
[b] The number in parentheses after the pit depth indicates that 1 or both specimens was punctured in the previous removal indicated by the number, (5) indicates that the pipe was punctured after 5 years, etc.

neath the coating, as it might also at points where the coating on a pipe is injured. The porcelain enamel was nearly as good. It is probable that some of the corrosion reported was the result of injuries in handling the specimens. However, as much greater care was taken than is practical with coatings on pipe lines, the corrosion resulting from injuries should not be entirely disregarded. The thick china-wood oil compound, W, prevented serious pitting in all soils. The fact that many of these coatings cracked and had a strong odor, and the blistering of the priming coat indicate that the coating had deteriorated. However, because of its thickness, it may remain helpful by separating the pipe from the soil for several more years. The thin coatings (D, E, F, J, and K) definitely deteriorated and are probably of little further use. Most of these coatings showed evidence of breakdown on earlier examinations.

(b) AFTER 4 YEARS OF EXPOSURE

Four of the five coatings buried in 1937 were made from Bakelite. The other was Koroseal. Tables 83 and 84 show the condition of the pipes beneath the coatings. Two coatings remained unaffected at one

TABLE 83.—*Condition of metal beneath Bakelite and Koroseal coating exposed for 4 years.*

U = No corrosion.
R = Pipe rusted.
M = Metal attack—pipe roughened by corrosion.
P = Definite pitting but no pits greater than 6 mils.
E = Ends corroded.

Soil No.	Specimen No.	Coating symbol					Uncoated low-carbon-steel pipe exposed 5 years,
		Bakelite base				Koroseal	
		L	M_1	M_2	N	P	N
53	1	U	R	M	R	.....	47
	2	R	R	M	R	.....	53
55	1	U	P	M	R	.....	48
	2	18	P	M	R	.....	66
56	1	R	P	58	P	.....	53
	2	R	P	M	P	.....	88
58	1	U	P	ME	P	.....	97
	2	12	15	25	R	.....	108
60	1	R	P	55	M	.....	18
	2	U	12	PE	R	.....	29
61	1	18	25	25	R	.....	23
	2	U	R	18	R	.....	85
62	1	U	R	M	R	15	66
	2	U	M	M	R	15	66
63	1	R	M	M	10	.....	33
	2	R	R	M	13	.....	38
64	1	R	U	P	U	.....	154+
	2	R	U	P	R	.....	154+
65	1	R	R	13	R	.....	79
	2	U	R	M	M	.....	69
66	1	M	R	12	M	12	154+
	2	22	P	28	P	P	154+
67	1	R	120	41E	35	45	84
	2	R	107	57E	30	50	154+
69	1	39	24	R	M	P	.....
	2	M	25	32	15	8	.....
70	1	U	R	PE	P	.....	.....
	2	R	R	16	P	.....	.....

test site. Corrosion had started beneath all the other specimens. The failures of the Bakelite coatings were usually accompanied by blistering. The failure of the Koroseal coating is characterized by a deterioration of the fabric to which Koroseal is applied.

TABLE 84.—*Summary of data on condition of coated pipe exposed for 4 years.*

[Figures in the table refer to the number of test sites. Data from specimens buried in 14 test sites except for P specimens, which were buried in 4 test sites. Poorer of the 2 specimens reported.]

Coating symbol	Condition of pipe				Coating blistered
	Unaffected	Rusted	Roughened	Pitted	
L	1	8	0	5	6
M 1	1	3	2	8	13
M 2	0	0	4	10	14
N	0	5	2	7	.....
P [a]	0	0	0	4	.....

[a] Poor bond between pipe and coating.

(c) AFTER 2 YEARS OF EXPOSURE

In 1939 two types of coatings were buried at 14 of the test sites, and an additional coating was placed at four of the sites. See table 12 for the maker's description of these coatings. Two specimens of each coat-

TABLE 85.—*Condition of coated pipe exposed for 2 years.*

M = Metal attack—pipe roughened by corrosion.
R = Pipe rusted.
P = Definite pitting but no pits greater than 6 mils.
U = No corrosion.

Soil No.	Specimen No.	Blue basic lead sulfates phenolic resin varnish paint, R	Plastic-treated fiber, S	Thiokol, T	Uncoated low-carbon-steel pipe N
53	1	M	P	.....	37
	2	M	P	.....	37
55	1	M	P	.....	40
	2	M	P	.....	42
56	1	12	25	.....	26
	2	M	20	.....	13
58	1	M	P	R	20
	2	M	P	R	16
60	1	R	M	.....	55
	2	R	M	.....	19
61	1	M	M	R	8
	2	M	M	U	13
62	1	M	10	R	68
	2	M	10	R	36
63	1	M	28	.....	21
	2	M	.....	.....	9
64	1	R	P	R	123
	2	M	20	R	138
65	1	M	P	.....	43
	2	M	P	.....	36
66	1	55	8	.....	71
	2	P	12	.....	61
67	1	M	27	.....	154+
	2	27	29	.....	154+
69	1	M	M	.....	.....
	2	M	M	.....	.....
70	1	10	8	.....	.....
	2	18	8	.....	.....

ing were removed from each test site in 1941. Table 85 shows the condition of each coated pipe after an exposure of 2 years. Only one specimen showed no sign of corrosion.

The lead-sulfate coating, R, blistered and became scaly. There was little adhesion between the plastic coating S and the pipe. The entire surface of each pipe coated with the plastic rusted. Soil indented the coating and adhered to it. In most soils the coating appeared to have rotted.

On each specimen of Thiokol-coated pipe there was a network of fine cracks which usually did not permit water to reach the pipe. In a number of cases the coating was chipped, possibly by the formation of rust beneath the coating.

IX. LABORATORY STUDIES OF CORROSION

1. DENISON CORROSION CELL

Denison [80, 81] has developed a corrosion cell for the study of corrosion phenomena in the laboratory. With this cell, the behavior of various soils and metals can be investigated under uniform conditions of moisture, aeration, etc., and the current through the cell can be regulated at will.

The cell consists essentially of two electrodes of the same metal separated by a layer of moist soil, which constitutes the electrolyte. Differential aeration of the two electrodes is brought about by making one of them more accessible to the air than the other, whereby the cell develops an internal electromotive force. It is often desirable, however, to control the current through the cell, which is done by means of an external battery and variable resistance. The construction of the cell is described in detail in Appendix 5. In the use of the Denison cell for investigating corrosion phenomena, the principal measurements made are of open-circuit potentials, short-circuit currents and simultaneous values of current and potential under various conditions.

Open-circuit potentials are measured with a potentiometer-voltmeter, which has the advantage that it draws no current from the circuit under test. Individual potentials of the anode and cathode are determined by using an auxiliary saturated calomel electrode connected through an agar-KCl bridge placed in contact with the soil through a hole in the bottom of the cell shown in figure 87 in Appendix 5.

Short-circuit currents are measured by means of a "zero-resistance" milliammeter in which the resistance of the instrument is compensated for by opposing the voltage drop in the instrument by an equal applied voltage.

The measurement of potentials in the cell while current is flowing is complicated by IR drops in the circuit. If the resistances were constant and accurately known, the IR drops could be calculated and proper corrections could be made, or, under certain conditions, errors from this source could be made small by placing the tip of the reference electrode close to the electrode whose potential is being measured, or by placing the reference electrode out of the path of current flow. According to Hickling [82], however, the error resulting from inclusion of some IR drops in the measured potential is seldom avoided, as there always is present a certain surface resistance which may be due to gas evolution, depletion of electrolyte in the layer in contact with the electrode, or, in the case of the anode, to a poorly conducting film. Wholly apart from the error due to the resistance of films, the high resistivity of soils

renders the measurement of potentials particularly difficult. Furthermore, marked variation of resistance with current may occur. The above methods are not readily applicable to the Denison cell.

Errors due to these unknown and variable IR drops can be practically eliminated by using a method developed by Hickling [82] and adapted to the Denison cell by Darnielle [83]. In this method, the current is periodically interrupted for very short intervals of time, and the potentials are measured during the period of interruption. If the interval of interruption is too long, the potential of a polarized electrode will change during the measurement, so that the observed value will not correspond to the potential existing while the current is flowing. The advantage of the Hickling method is that the time during which the current is interrupted can be made very short (of the order of 10^{-5} seconds), so that errors due to depolarization are very small. Details of the method are given in Appendix 6.

From data obtained with the corrosion cell, various relationships and critical values can be determined which appear to be related to the type of control, the rate of corrosion, the relative corrosiveness of different soils, and the relative resistance to corrosion of different metals. The principal relationships which have been useful in this connection are represented by current density-potential curves and potential-time curves.

The rate of corrosion of steel under many soil conditions appears to be controlled chiefly by the rate at which the cathodic areas are depolarized. In fact, in the absence of conditions which favor the formation and development of protective anodic films or of corrosion products in immediate contact with the corroding area, the progress of corrosion in soils is probably determined by the rate of the cathode reaction. Corrosion under such conditions is said to be under cathodic control. On the other hand, if a more or less protective film develops on the anode, the rate of corrosion tends to be controlled by the reaction at the anode and the corrosion is then said to be under anodic control. The type of control under which corrosion proceeds, that is, whether anodic or cathodic has been shown by Bannister and Evans [84], Burns [85], and Brown and Mears [86] to be indicated by the relation between the current (or current density) and the potential of the anode and cathode of a corroding specimen. Current density-potential curves that are typical of cathodic control are shown in figure 42. It will be seen that the change in the cathode potential with increasing current density is much greater than the corresponding change in anode potential. This is particularly well illustrated by the curve for soil 57. A current density of 17 ma/dm^2 raised the potential of the anode by only 0.05 volt, whereas the potential of the cathode was lowered by 0.20 volt. Curves for metals corroding under anodic control show that the change in potential with increasing current density is greater for the anode than for the cathode.

If it were not for the high internal resistance of the cell, which limits the value of the current on short circuit, the rate of corrosion could be determined simply by measuring the short-circuit current at a suitable stage of corrosion. It is preferable, however, to eliminate the effect of resistance. This is accomplished by making use of the current density-potential curves. As the current density is increased, the potentials of the anode and cathode approach the same value. At the point where the two curves intersect, the cell is completely polarized, the internal potential difference is zero and the applied electromotive force just balances

the internal IR drop. The potential of the electrodes at this point is known as the corrosion potential. The associated current density is the limiting value for the particular combination of soil and electrodes and corresponds to the current for the maximum rate of corrosion. The interpretation of current-density–potential curves as indicative of rate of corrosion has been discussed by Evans [87], Evans and Hoar [88], Burns [85], and others.

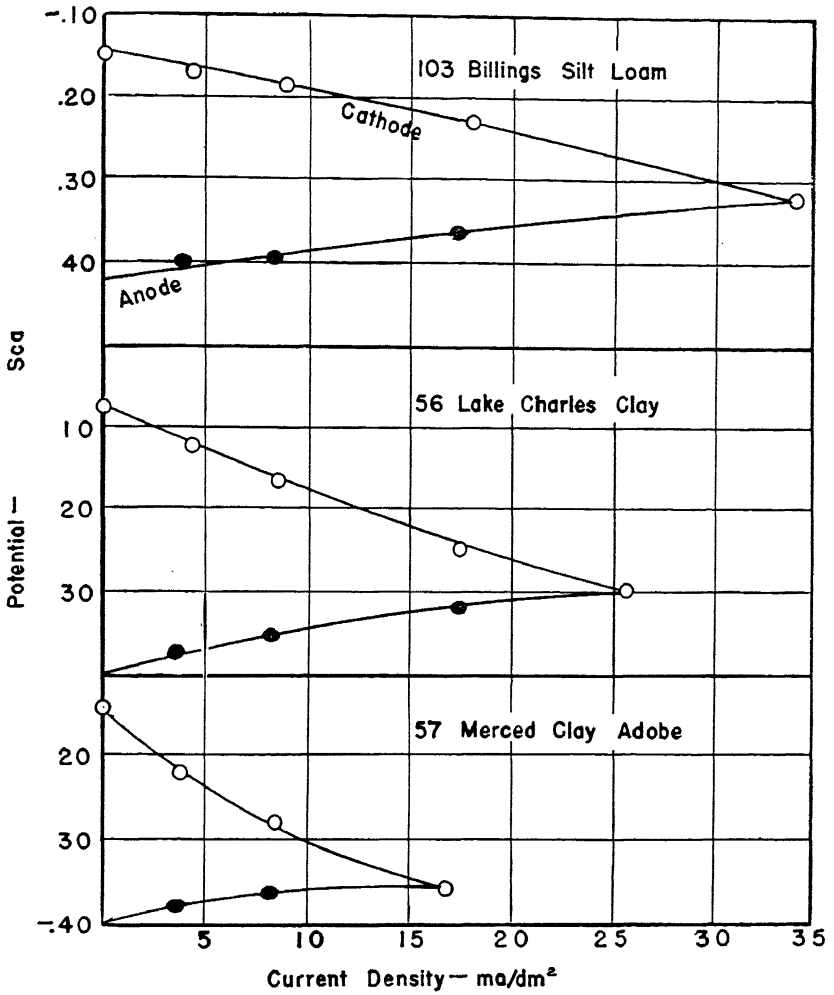

FIGURE 42.—*Current-density–potential curves.*

Metals such as stainless steel, lead, copper and copper alloys, which tend to form protective oxide films in soils, develop only small potential differences and as such a cell has a high resistance only a negligible current flows between the electrodes. Under these conditions, the corrosion is due almost entirely to local cell currents and obviously the short-circuit current would not be sufficient to account for the observed corrosion. If it were not for local action, it should be possible to stop corrosion at the anode by opposing to the potential difference developed internally

an external electromotive force just sufficient to prevent current from flowing away from the anode. However, in order to completely suppress the local action, which is the principal cause of corrosion in the cell when on open circuit, it is necessary to apply a greater electromotive force so that current flows into the anode. The minimum value of current required to protect the electrode from corrosion is called the protective current.

The local-cell theory of Müller [89] indicated that, with cathodic control, the protective current should be equal to the corrosion current. Other investigators have shown that the protective current is equal to the corrosion current under certain conditions. For example, Gatty and Spooner [90] found good agreement between values which they obtained for the "critical," that is, protective, current for copper in dilute sulfuric acid and in neutral salt solutions and the currents calculated from data available in the literature on corrosion under similar conditions. According to Mears [91] the amount of current required to prevent corrosion is equal to the corrosion current only if the corrosion reaction is completely determined by oxygen diffusion, that is, by cathodic control.

Evans, Bannister, and Britton [92], working on the current-potential relation of various metals when made cathodic in an aerated solution of 0.1 N potassium chloride, found that, at current densities below the minimum value required to protect the metals cathodically, the potential of the cathode remained unchanged as the current density was increased. At current densities greater than the protective value, the potential of the cathode increased logarithmically. This behavior may be explained by assuming that the plate was originally made up of anodic and cathodic areas and that the latter were covered by a high-resistance film. Current therefore flowed only to the anodic areas until they were destroyed by the neutralizing of the local currents, after which the entire plate becomes cathodic. Ewing [93] has utilized this principle for determining the protective current by plotting the potential of the cathode against the logarithm of the applied current.

2. BEHAVIOR OF STEEL IN VARIOUS SOILS

Denison and Darnielle [94], using the corrosion cell, have investigated the behavior of steel in various soils when it corroded under cathodic control. Measurements of the corrosion potential were made at intervals during a period of 2 weeks. During the test period, the cells were kept on short-circuit and maintained at a temperature of 25°±0.5°C. The moisture content of the soils was maintained constant by placing the cells in separate friction-top cans in which a small quantity of water was placed in such a way that it did not come into direct contact with the cells.

Typical corrosion-potential–time curves are shown in figure 43. It will be observed that after the first few days the corrosion potential became practically constant. In a few soils, a slight regular increase in the corrosion potential was noted even at the end of the test period. This is attributed chiefly to the fact that the potential of the cathode tends to become more positive with time. In all the soils studied, the corrosion potential was more positive than the open-circuit potential of the anode. Brown and Mears [86] have pointed out that the potential of a galvanic couple can be identical with the open-circuit potential of the anode only if there is no anodic polarization. The fact that in many soils the polarization curve for the cathode is very flat causes the potential of the short-circuited electrodes to become more cathodic.

Typical results of measurements of open-circuit potentials of the anode and cathode over a test period of 2 weeks are shown in figure 44. The marked change in the potential of the cathode (which becomes more positive) indicates that the potential of that electrode tends to approach the potential of the oxygen electrode in the particular environment.

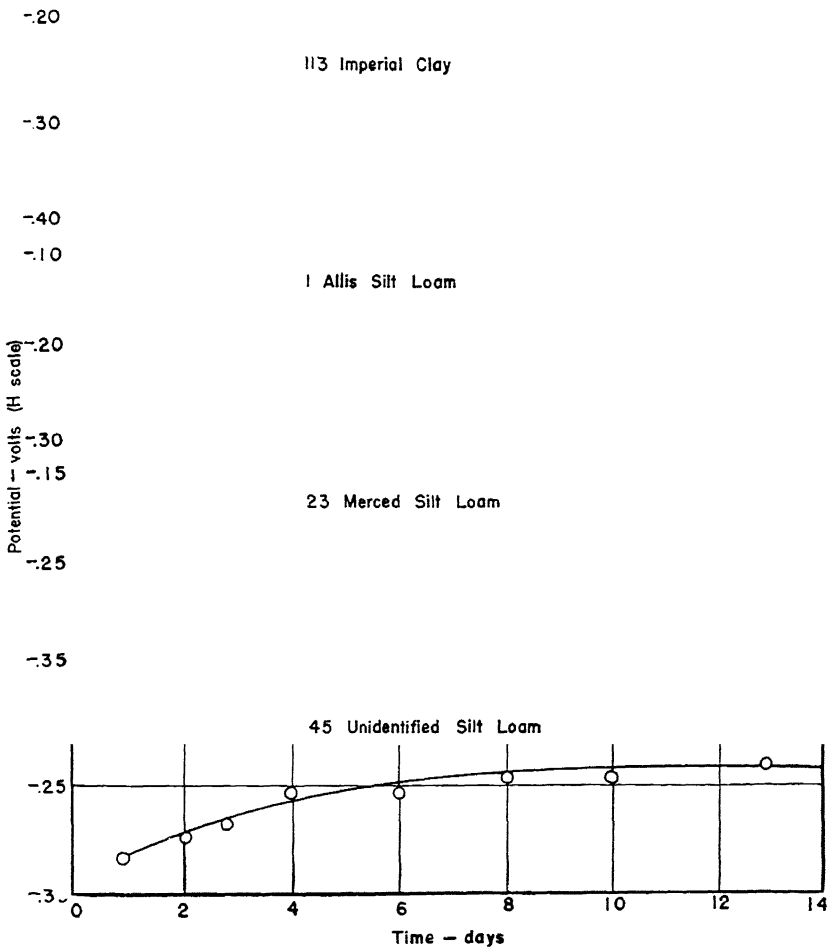

FIGURE 43.—*Relation between corrosion potential and time.*

The reason the latter potential is not reached is that imperfections in the protective oxide film expose the underlying metal. During the initial period of exposure, anodic areas develop on the perforated electrode as well as on the solid disk. As the solid disk is less accessible to air, the areas surrounding the points of attack on the disk soon become cathodically polarized. As a consequence, current leaving the anodic area on the solid disk flows to the perforated disk, where, because of the relatively greater concentration of oxygen, cathodic polarization is less. The extension of the cathodic areas on the perforated disk diminishes the number of anodic areas because the cathodically produced OH ions in the presence of oxygen precipitate ferric hydroxide in immediate contact with the corroding areas and thereby effect repair of the film.

In addition to the measurement of potential, daily observations of the short-circuit current of the cells were made. The maximum current developed usually within 18 to 24 hours, although in a few cells the current increased gradually for a week or longer.

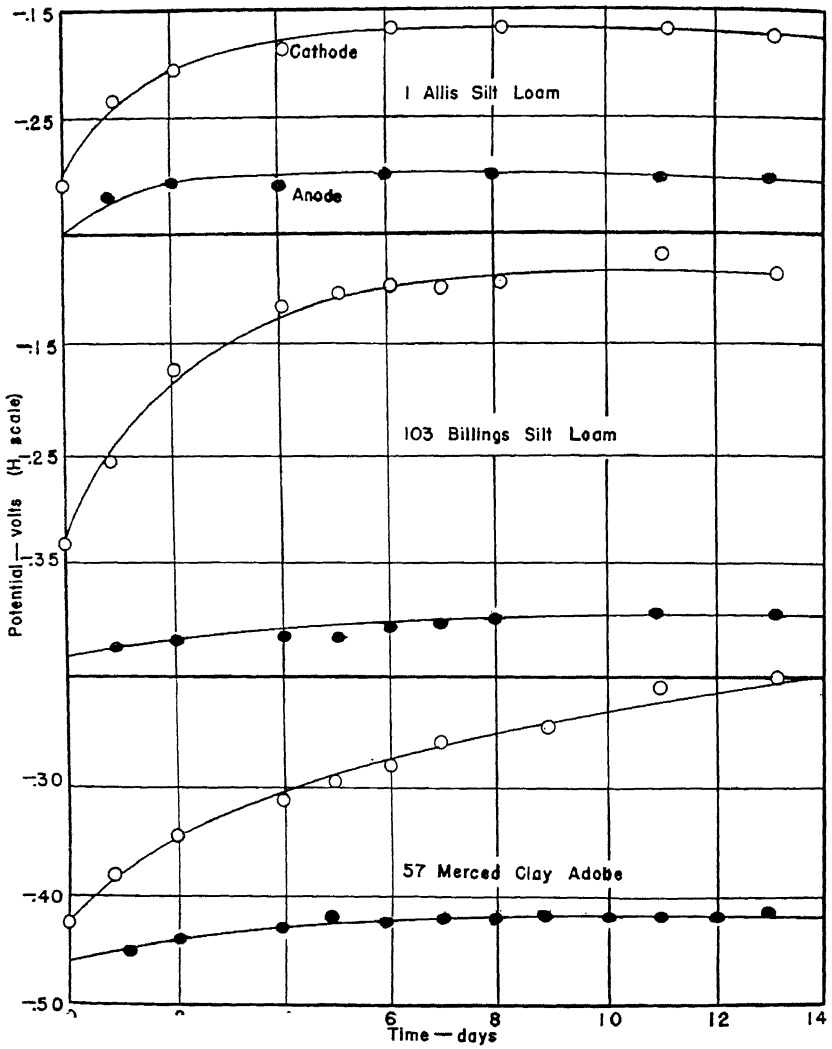

FIGURE 44.—*Potential-time curves for the anode and cathode.*

In order to correlate the results of the various electrical measurements with the corrosion, the loss of weight of the anodes was determined. The results are summarized in table 86, in which the soils are arranged in the descending order of their corrosiveness as indicated by the loss of weight during the 2-week test period. It can be seen that there is a rather definite correlation between the loss of weight and either the current at corrosion potential or the maximum short-circuit current. The ratio between these two currents is fairly constant in soils of low resistivity, and tends to increase in soils of higher resistivity, as would be

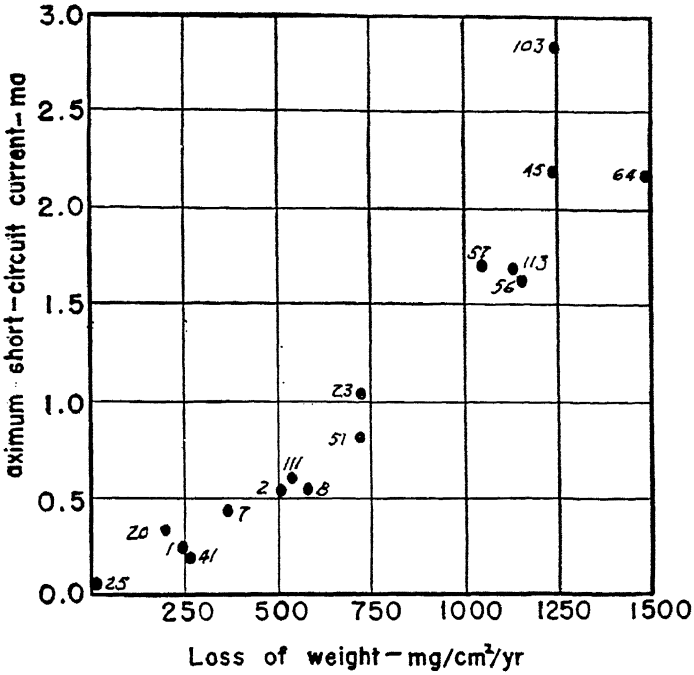

FIGURE 45.—*Correlation between maximum short-circuit current and loss of weight of the anodes.*

expected. The correlation between the maximum short-circuit current and loss of weight is shown in figure 45. The somewhat erratic nature of the results can be ascribed to the unequal ratio of the maximum to the average current for the different soils.

TABLE 86.—*Corrosiveness of soils as indicated by electrical measurements and loss of weight of the anodes.*

Soil No.	Soil type	Maximum open circuit voltage [a]	Corrosion potential [b]	Current at corrosion potential	Maximum short-curcuit current	Loss of weight [c]
		v	*v*	*ma*	*ma*	(*mg/cm²*) *yr*
64	Docas clay	0.31	0.34	2.72	2.19	1,475
103	Billings silt loam	.30	.32	3.86	2.85	1,230
45	Unidentified alkali soil	.38	.29	2.55	2.20	1,230
56	Lake Charles clay	.37	.29	2.92	1.64	1,150
113	Imperial clay	.38	.31	2.90	1.70	1,130
57	Merced clay adobe	.30	.35	2.00	1.70	1,040
23	Merced silt loam	.34	.22	1.88	1.05	722
51	Acadia clay	.12	.31	1.20	0.80	708
8	Fargo clay loam	.12	.37	0.78	.55	580
111	Fresno fine sandy loam	.16	.21	1.20	.60	534
2	Bell clay	.14	.33	0.90	.54	504
7	Unidentified soil	.14	.24	.50	.42	370
1	Allis silt loam	.14	.22	.60	.23	244
41	Summit silt loam	.07	.26	.40	.20	214
20	Manoning silt loam	.20	.30	.67	.32	202
25	Miami clay loam	.01	.32	.005	.003	16

[a] Potential between anode and cathode of corrosion cell on open circuit.
[b] Potential at intersection of current-density–potential curves.
[c] Calculated from results in a 2-week run.

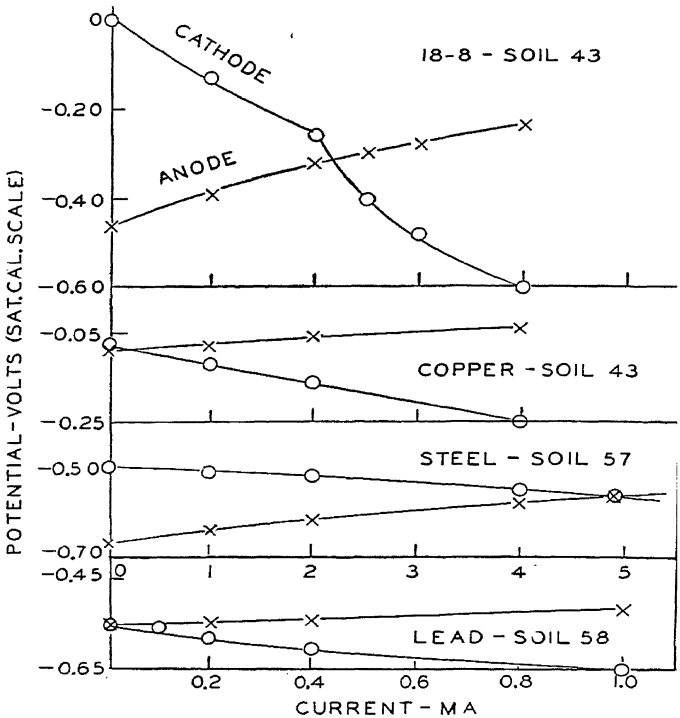

FIGURE 46.—*Corrosion under cathodic control.*

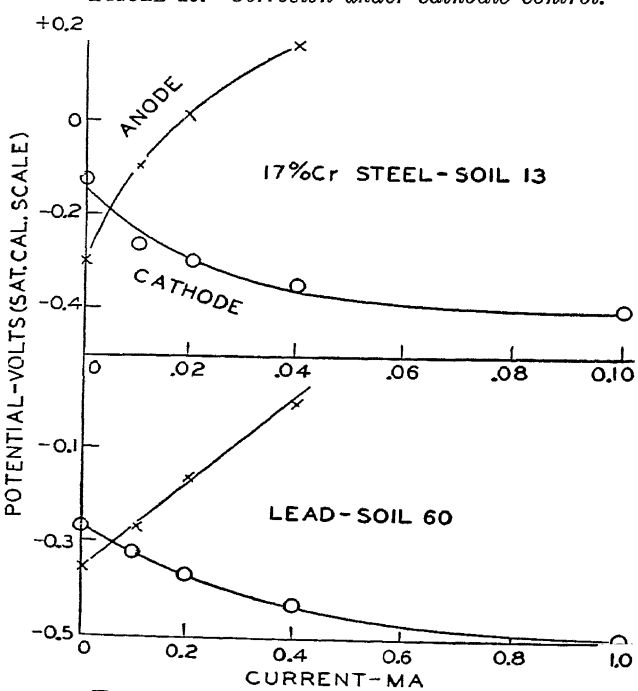

FIGURE 47.—*Corrosion under anodic control.*

3. BEHAVIOR OF DIFFERENT METALS IN VARIOUS SOILS

In view of the extensive use of metals other than iron or steel, such as copper, brass, lead, zinc, etc., Denison [95] has used his corrosion cell for the investigation of the behavior of several different metals. In most soils, the corrosion of steel is under cathodic control. However, if a protective film develops on the anode, the corrosion tends to be anodically controlled. The type of control for the various metals in different soils was determined by inspection of the current-potential curves of the separate electrodes. The typical curves shown in figures 46 and 47 indicate corrosion under cathodic and anodic control, respectively.

It is of interest to consider the behavior of lead, as illustrated by the current-potential curves for lead in figures 46 and 47, with respect to the environmental conditions of Houghton muck (soil 58) and Rifle peat (soil 60). Both soils are organic, having been derived from the decomposition of vegetable matter. Reference to the composition of the soluble material in the soils (table 20) shows that both soils are very acid and that soil 60 is extremely high in sulfates. The slight anodic polarization shown by lead in soil 58 (figure 46) is consistent with the known corrosive action on lead of organic acids produced in the decomposition of wood and other organic matter. The organic acids maintain a low concentration of lead ions at the anode. The corrosion of lead in soil 60 was inhibited by the marked polarizing action of sulfate ions, exhibited by the curve for the anode in this soil (figure 47).

The curves for stainless steel of the 18–8 variety in soils 43 and 13 represent the behavior of this alloy in the active state (figure 46) and in the passive state (figure 47). While in the passive state, even a slight flow of current is seen to have a marked effect on the potential of the anode. However, with the metal in the active state, the anode exhibits the characteristic behavior of ordinary carbon steel. The shift from the passive to the active condition in soil 43 resulted from the inability of the oxide film to maintain a state of repair in a reducing environment high in chlorides and sulfates. In figure 46 the change in curvature for the cathode at 2 milliamperes corresponds to the shift from the oxygen electrode reaction to that of the hydrogen electrode. Curves of this type have been discussed by Hoar [96].

In table 87 is shown the type of control under which the materials corrode in the different soil environments. The corrosion of zinc and steel is under cathodic control in all of the soils because, in the presence of chloride, sulfate, carbonate, and bicarbonate ions in an environment deficient in oxygen, the primary reaction products of steel and zinc are soluble and consequently diffuse readily away from the anode surface. Under these conditions, a fairly large negative potential can be maintained at the anode, even at relatively high current densities. However, in very porous soils which are either strongly alkaline or are deficient in soluble salts, the type of control of steel and zinc shifts from cathodic to anodic. The fact that the corrosion of zinc is generally under cathodic control has naturally an important bearing on its use as a protective coating for steel and as an anode in cathodic protection installations.

Following the procedure of Ewing [93] for determining protective current, the potential of the cathode was plotted against the logarithm of the applied current for a variety of metals in Docas clay (soil 64). The curves are shown in figure 48. Most of the curves are composed of two parts, the first being horizontal (or nearly so) and the second being linear with a negative slope. At the higher currents, the cathode is polarized to such values that hydrogen evolution begins and the potential

follows the linear hydrogen overvoltage curve. Similar curves have been obtained and discussed by Gatty and Spooner [90] and by Hoar [96]. In the case of a few metals in certain soils, the first part of the curve has an appreciable negative slope. This change in potential may have resulted from a partition of the applied current such that a certain fraction flowed to the cathodic areas. Under such conditions, which would be caused by the high resistance of small anodic areas, the protective current would be greater than that associated with corrosion.

TABLE 87.—*Control of the corrosion rate of metals in different soil environments.*

Material	Environment							
	Alkali carbonate		Chloride	Sulfate	Chloride and sulfate	Reducing, with organic acids	Reducing, with organic acids and sulfate	Reducing with organic acids chloride and sulfate
	Good aeration	Poor aeration						
	Soil number							
	13	[a] 23	64	57	56	58	60	43
Low-carbon steel	Cathodic [b]	Cathodic	Cathodic	Cathodic	Cathodic	Cathodic	Cathodic	Cathodic
Steel with 17% Cr	Anodic	Anodic	Anodic	Anodic	Anodic	Anodic	Anodic	....do..
18–8 steel	....do...	....do..	....do..	....do..	....do..	....do..	....do..	....do..
Copper	....do...	....do..	....do..	....do..	....do..	Cathodic	Cathodic	....do..
Brass (60–40)	....do...	....do..	....do..	....do..	....do..	....do..	....do..	....do..
Zinc	Cathodic	Cathodic	Cathodic	Cathodic	Cathodic	....do..	....do..	....do..
Lead	Anodic	Anodic	Anodic	Anodic	Anodic	....do..	Anodic	Anodic

[a] Sulfates also present.
[b] Anodic with exceptionally good aeration.

4. COMPARISON OF LABORATORY DATA WITH THE RESULTS OF FIELD TESTS

In view of the fact that conditions in the field are not uniform, an exact correlation between the results of laboratory tests and those obtained in the field should not be expected. The laboratory tests, however, should be expected to give a general indication as to whether under given field conditions corrosion will be severe or negligible. In order to determine to what extent this is true, the results of the laboratory tests have been compared with those obtained in the field for the same metals buried in the same soils. The corresponding values are given in table 88. In order that the laboratory data may be made comparable for the different materials, the loss of weight corresponding to the selected value of corrosion current or protective current was calculated. The values thus obtained can be compared with the actual losses during the exposure period of 2 weeks in the case of the cells that had a definite polarity. As the cell current was necessarily less than the current at corrosion potential, on account of the IR drop in the cell, the calculated losses are greater than the actual losses, except in cells of very low resistance.

Generally speaking, the current at corrosion potential can be taken as the measure of the rate of corrosion whenever corrosion proceeds under cathodic control. An exception must be made, however, for two organic soils, Houghton muck (soil 58) and Rifle peat (soil 60). On account of

the very high water content on these soils, which approached saturation, the perforated-disk cathode could not develop a potential sufficiently noble to overcome the resistance of the soil. Whenever comparisons are possible, the agreement between the values of protective current and the current at corrosion potential is generally good, which indicates that protective current can also be taken as a measure of corrosion rate, at least when the rate is controlled cathodically. The few cases of poor agreement can be reasonably accounted for.

The field data given in table 88 show the average rate of loss of weight and rate of maximum penetration, usually of two specimens of each material after exposure to the various soils for approximately 8 years.

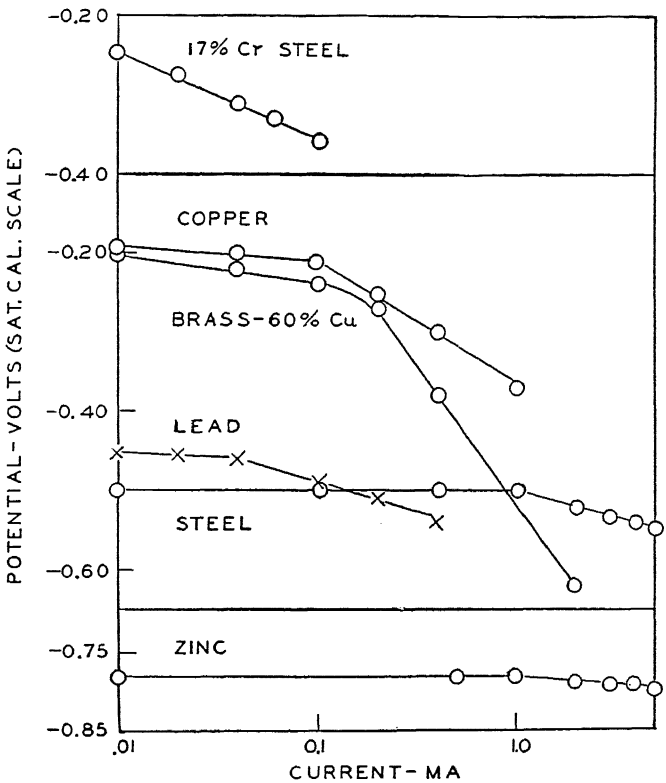

FIGURE 48.—*Current-potential curves for the cathode in Docas clay.*

When data for more than one grade of a given material were available, as was the case with lead and zinc, the values for all grades were averaged. Because of the marked tendency for the rate of corrosion to decrease with time of exposure under certain environmental conditions, the rates given for lead and zinc after exposure for 2 years are not strictly comparable with the values given for the usual 8-year period.

To facilitate the comparison between the field and laboratory data, the relative order of the metals with respect to their resistance to corrosion is given in the table. The correlation of the laboratory data with loss of weight in the field is somewhat better than with the rate of pitting, which seems reasonable in view of the fact that a given loss in

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TABLE 88.—*Comparison of corrosion data from laboratory and field tests.*

Material	Type of control: C=cathodic A=anodic	Laboratory data				Field data			Order of corrodibility based on—		
		Current at corrosion potential	Protective current	Calculated loss in weight	Actual loss in weight	Approximate exposure	Rate of loss in weight [a]	Rate of pitting	Calculated loss of weight in laboratory test	Rate of loss of weight field test	Rate of pitting in field test
SOIL 13, HANFORD FINE SANDY LOAM											
		ma	*ma*	*g*	*g*	*yr*	*(oz/ft²)/yr*	*Mils/yr*			
Steel	C	0.70	0.50	0.245	0.137	6	1.24	11.8	5	6	6
Zinc	C	1.80	.30	.738	.542	8	0.31	6.3	6	5	5
Copper	A	.....	.28	.111	.....	8	.03	1.0	3	4	3
Brass (60–40)	A	.....	.32	.127	.....	8	.10	1.0	4	3	3
Lead	A	.....	.06	.077	.....	6	.....	0	2	[b] 2	1
17% Cr steel	A	.....	.....	.....	.....	8	[c] .005	[c] 0	1	1	1
SOIL 23 (70), MERCED SILT LOAM											
Steel	C	1.30	1.30	0.455	0.457	8	2.45	19.6	5	6	5
Zinc	C	2.40	.70	.984	.719	2	0.74	20.0	6	4	6
Copper	A	.....	.03	.012	.....	8	.13	1.9	3	3	4
Brass (60–40)	A	.....	.06	.024	.....	8	.75	1.3	4	5	3
Lead	A	.....	0	0	.....	8	.03	0	1	2	1
17% Cr steel	A	.....	0	0	.....	.....	.....	.....	1	[b] 1	[b] 1
SOIL 43, TIDAL MARSH											
Steel	C	1.00	1.20	0.350	0.246	8	1.40	11.0	4	7	6
Zinc	C	3.60	.....	1.476	.927	8	0.21	8.1	7	4	5
Copper	C	0.40	0.42	0.167	.114	8	.60	[d]	3	5	[b] 3
Brass (60–40)	C	0	.16	.064	.010	8	.03	1	1	2	1
Lead	A	.18	.08	.103	.106	8	.05	2.3	2	3	4
17% Cr steel	C	3.40	.11	1.190	.462	8	[c] .67	[c] 30.0	6	6	7
18–8	C	2.20	.33	0.770	.330	8	[c] .0003	[c] 1	5	1	1
SOIL 56, LAKE CHARLES CLAY											
Steel	C	0.93	0.90	0.326	0.334	7.5	2.79	16.5+	6	7	6
Zinc	C	2.20	2.70	.902	.947	2	0.84	9.0	7	6	5
Copper	A	.....	0.035	.014	.....	7.5	.08	1.1	3	3	3
Brass (60–40)	A	.....	.04	.016	.....	7.5	.09	1.0	4	4	2
Lead	A	.....	.10	.129	.....	2	.15	24.5	5	5	7
17% Cr steel	A	.....	0	0	.....	.....	.....	.....	1	[b] 1	[b] 1
18–8	A	.....	0	0	.....	7.5	0.005	3+	1	2	[illegible]

SOIL 57, MERCED CLAY ADOBE

Steel	C	4.9	.....	1.715	0.627	5	1.66	19.0	7	7	7
Zinc	C	2.35	2.15	0.964	1.320	.....	.....	.....	6	[b] 6	[b] 6
Copper	A	.....	0.08	.032	.....	5	0.02	1.1	5	4	3
Brass (60–40)	A	.....	.07	.028	.....	5	.30	4.2	4	5	4
Lead	A	.....	0	0	.....	.....	.....	.....	1	[b] 1	[b] 1
17% Cr steel	A	.....	0	0	.....	5	.018	6.5+	1	3	5
18–8	A	.....	0	0	.....	5	.0002	1.0	1	2	2

SOIL 58, MUCK

Steel	C	1.30	1.60	0.455	.....	7.6	2.76	[f] 14.4	6	6	6
Zinc	C	0.39	0.25	.160	.....	8.0	[f] 0.54	[f] 4.1	5	4	4
Copper	C	.....	.11	.044	.....	7.6	.22	1.8	2	2	3
Brass (60–40)	C	.....	.19	.076	.....	7.6	.61	1.1	3	5	2
Lead	C	.....	.10	.129	.....	8.0	[f] .27	[f] 0.7	4	3	1
17% Cr steel	A	.....	0	0	.....	8.0	[ef] .035	[ef] 10.2	1	1	5

SOIL 60, RIFLE PEAT

Steel	C	.....	0.84	0.290	.....	7	1.45	2.5	6	6	5
Zinc	C	.....	.80	.328	.....	2	3.03	31.8	7	7	7
Copper	C	.....	.28	.111	.....	7	0.14	1.2	3	4	4
Brass (60–40)	C	.....	.34	.135	.....	7	.19	1.1	4	5	2
Lead	A	.....	.05	.065	.....	2	.07	10.5	1	3	6
17% Cr steel	A	.....	.56	.196	.....	7	.045	1.1	5	2	2
18–8	A	.....	.26	.091	.....	7	.0002	1.0	2	1	1

SOIL 64, DOCAS CLAY

Steel	C	2.2	1.8	0.770	0.627	7	4.88	21.1+	6	7	7
Zinc	C	7.0	.....	2.870	1.413	2	0.51	8.5	7	5	4
Copper	A	.....	0.10	0.040	.....	7	.21	2.0	4	4	3
Brass (60–40)	A	.....	.18	.072	.....	7	1.34	0.8	5	6	1
Lead	A	.....	.03	.039	.....	2	0.10	16.0	3	3	6
17% Cr steel	A	.....	.005	.002	.....	7	.06	9+	1	2	5
18–8	A	.....	.004	.002	.....	7	.0004	1.1	1	1	2

[a] To convert these values to (g/dm²)/yr, multiply by 3.05.
[b] Value assumed, to facilitate comparison of data.
[c] Data for steel with 26% Cr.
[d] Uniform corrosion.
[e] Data for similar soil 63.
[f] Data for similar soil 29.

weight might be distributed fairly uniformly over the surface, as was the case with copper in soil 43, or it might be confined to a relatively few pits, as in the case of the stainless steels.

Both the laboratory tests and the field data indicate that the corrosion of steel is relatively severe in all the soils. The corrosion of zinc relative to that of steel is considerably greater in the laboratory than in the field. In fact, the laboratory data indicate that zinc is corroded even more rapidly than steel. In the field, the steel corroded more rapidly. Evidently the separation of the electrodes in the cell accelerated the corrosion of the zinc. In the field, the concentration of the alkali at the cathodic areas was greater, so that the zinc hydroxide which precipitated as an adherent film tended to prevent the extension of the anodic areas and the consequent increase in the corrosion current. In the corrosion cell, the electrodes were far enough apart so that the anodic areas would be unaffected by the spreading of alkali at the cathode. The laboratory data might better be taken to represent the behavior of zinc as the anode in a galvanic cell, for example, in the protection of steel cathodically. It is in connection with the protection of steel against corrosion, either as a metallic coating or as a separate anode in connection with cathodic protection, that the behavior of zinc in soils is of the most practical importance.

The relative corrodibility of copper and 60–40 brass in general agrees qualitatively in the two series of tests. However, the marked differences occasionally observed in the corrosion rates of these materials in the field tests, as in soils 23 and 57, are not reflected in the laboratory data. Evidently the electrodes in the corrosion cell are not as much affected by dezincification as in the field tests. It is note-worthy that the superiority of the low-copper brass in the Tidal marsh soil (43), which contains sulfides, is indicated by both tests.

The corrosion rates of lead at certain of the test sites are subject to the limitation of having been calculated from exposures of only 2 years. If allowance is made for the probable decrease in the corrosion rate with time in these soils, both field and laboratory data may be taken to indicate low rates of corrosion of lead in soils containing high concentrations of chlorides, sulfates, or carbonates.

X. SOIL SURVEYS AND TESTS

1. ESTIMATION OF THE CORROSION TO BE EXPECTED IN SOILS

One of the most important considerations in connection with the laying of a pipe line is the amount of protection that should be provided against corrosion. It has already been shown that the various soils differ with respect to their corrosive action on buried metal. Obviously, therefore, an early step should be a survey to estimate the amount of corrosion to be expected in various parts of the territory in which the line is to be laid. If it were true that soils attack metals in much the same way as chemicals do and some one measurable property of the soil could be taken as a criterion of its corrosivity, such a survey would be a comparatively simple matter. Unfortunately, however, the inherent chemical nature of the soil is not always the most important factor involved, and several others must be considered. Furthermore, as soils are seldom homogeneous throughout more than a relatively small volume, a given sample may be more or less corrosive than a similar sample taken only a few feet away. Also, a single test on a composite sample would present merely the average of its components, whereas it is the

maximum corrosiveness of a soil that usually determines its destructive effect. For these reasons, and realizing also that some of the characteristics of the soil are altered in the sampling or testing process, it is evident that the results of a single test may be misleading, and even many tests cannot be expected definitely to indicate the time when the first failure of a pipe will occur. On the other hand, a series of tests on an adequate number of samples properly taken, or a soil survey in which observations are made at frequent intervals, will furnish data from which reliable estimates can be made concerning the performance of a pipe line exposed to the soils thus examined. A soil survey, including the taking of the samples, should preferably be made by an experienced engineer, who should also be responsible for the interpretation of the results because proper conclusions depend not only upon the numerical data, but also upon observations of local conditions, which are often difficult to express definitely. An experienced engineer familiar with soil conditions and their relation to pipe line corrosion may be able to make a better estimate of the corrosive areas from visual observation alone than can be made by a technician skilled only in laboratory methods. The best results are to be obtained by a combination of tests and experience.

2. FIELD TESTS

(a) RESISTIVITY

The most common criterion of the corrosivity of a given soil is its resistivity. This depends quite largely upon the nature and amount of dissolved salts in the soil, and is also affected by the temperature and moisture content of the soil. Obviously, the resistance of the electrolyte is one of the factors that affect the flow of the current associated with corrosion. If other factors are constant, there is a relation between soil resistivity and corrosion, as indicated in table 89, which presents data obtained by Denison and Ewing [40].

TABLE 89.—*Repairs to pipe lines in different types of soils as related to their resistivity.*

[Total acidity 15 to 18 mg =eq per 100 g of soil]

Soil type	Resistivity	Pipe line repaired
	Ohm-cm	*Percent*
Lordstown fine sandy loam	11,450	3.3
Wooster loam	8,002	6.0
Volusia silt loam	5,473	13.6
Mahoning silt loam	4,903	20.9
Miami silt loam	3,982	22.8
Nappanee clay loam	1,009	57.0

The soil is an electrolyte, and the precise measurement of its resistivity requires carefully designed apparatus and carefully planned procedures. If direct current is used, polarization of the electrodes will affect the results. If alternating currents are employed, the apparatus must compensate for inductance and capacity, which vary with frequency. Also, corrections for the temperature and moisture content of the electrolyte must be made. However, as two samples of soil are seldom

identical, and as the factors other than resistivity are rarely constant, an approximate value of resistivity is usually sufficient. The following methods of determining in the field the resistivity of a sample of soil under the conditions existing at the time of the measurement are sufficiently accurate for most corrosion engineering purposes.

(1) *Shepard's Soil-Resistivity Apparatus.*—Of the several pieces of apparatus used for rough determinations of soil resistivity by corrosion engineers, Shepard's [97] apparatus, as shown in figure 49, is probably most widely used. The apparatus consists of small electrodes attached to insulating rods. The electrodes are connected to a battery and a milliammeter and thrust into the soil to be tested. Shepard describes the apparatus as follows: "The anode is an iron cone of one-half inch (1.27 cm) base and one-quarter inch (6.3 mm) height. The cathode, also of iron, is a frustum of a cone 2⅝ inches (6.7 cm) long, three-quarters inch (1.9 cm) lower base, one-eighth inch (3 mm) upper base. The point is ground or turned to a 1/16-inch (1.5 mm) radius. A three-volt battery of two flashlight dry cells is used, the positive pole being connected through a switch to the smaller electrode or anode."

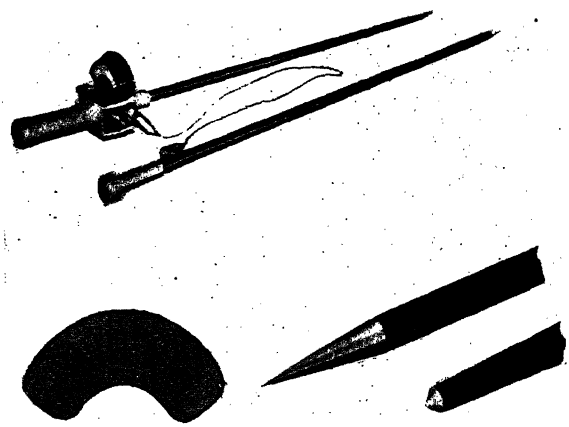

FIGURE 49.—*Shepard soil resistivity meter.*

A milliammeter having ranges of 25 and of 100 milliamperes is employed. The 25-milliampere range is good for resistivities down to 370 ohm-cm, whereas the 100-milliampere range is good for resistivities between 400 and 100 ohm-cm. The scale of the meter can be graduated directly in ohm-centimeters. A multiplier coil is included in the meter so that the voltage of the battery can be checked from time to time. With such an instrument, the soil resistivity in ohm-centimeters is equal numerically to approximately three times the measured resistance between the electrodes when they are separated in the earth about 8 inches (20 cm) or more. The resistivity meter measures the resistivities of sodium chloride solutions ranging from 100 to 10,000 ohm-centimeters, with an accuracy of about 6 percent.

The accuracy of the reading depends on the condition of the battery and on the resistance of the contacts between the electrodes and the soil.

The apparatus cannot be used in very dry or rocky soil. Because the apparatus measures the resistivity of only a small volume of soil, a single reading may not be indicative of the resistivity of the average soil throughout the region of the test. This objection can be overcome by making several tests in different holes. The apparatus is easily portable and inexpensive, and a large number of observations can be made in a few hours either in the walls and bottoms of trenches or in holes driven in the ground. The apparatus may be purchased from either of two manufacturers or be constructed from directions published by Shepard [97].

(2) *Wenner's Four-Terminal Method.*—The average resistivity of a large volume of earth can be determined from the surface of the ground by a method developed by Wenner [98] and applied by means of (1) the McCollum earth current meter, (2) the Megger, or (3) by a voltmeter, ammeter, and battery. Four contact points are placed in the earth at equal distances a in a straight line. An alternating or periodically reversed current is caused to flow between the outer electrodes, and the resulting differences of potential between the inner electrodes is observed. If the depth to which the electrodes is inserted in the ground is small compared with the distance a, the effective resistance between the potential electrodes is given by the equation $R=r/2\pi a$, where r is the resistivity of a unit volume of soil in terms of the unit in which a is measured. According to Wenner, the measured resistivity depends mainly on the resistivity of the portion of earth situated between the inner electrodes and having a cross section equal to the square of half the distance between the outer electrodes.

According to Rooney [99], who describes apparatus for measuring earth resistivity, the resistivity determined by this method is a general average value in which the resistivity near the line of the terminals is more heavily weighted. He says that, roughly speaking, the effect of material, at a distance (a) equal to the distance between adjacent terminals, is found to be so small that the effect of materials beyond it is negligible.

Biddle [100], who has designed an apparatus for field measurements of soil resistance by the four-terminal method, says that under conditions specified above the resistance measured is that of a half cylinder of length a, and radius $2a$. The four-terminal method has been used for studying the changes in soil resistivity with depth and, hence, for determining the desirable length of vertical anodes or the depth at which they should be placed. One corrosion engineer [101], employing this method, uses a B battery for the source of current and reduces polarization errors by using a vacuum-tube voltmeter for the potential measurement.

(3) *Electrolytic-Bridge Method.*—The electrolytic-bridge method for measuring soil resistivity is employed by the U. S. Department of Agriculture [102]. Fifty milliliters of soil is saturated with distilled water and put into a specially designed vessel containing two electrodes, and the resistance between the electrodes is measured by means of a Wheatstone bridge excited by a vibrator. A telephone receiver is used as a null indicator. By means of tables, the resistivity and salt content are determined from the measured value of resistance. The apparatus is easily portable and can be purchased from an electrical supply house. The determination of the resistivity of the soil when saturated has the advantage of reproducibility of condition and avoids the problem of the proper compactness of the sample. The question as to whether or

not the sample is representative of local conditions remains. Also, if desert soils are involved, the resistivity thus observed may be quite different from that of the dry soil from which the sample was taken.

(4) *Radio Balance.*—Another method of making a soil-resistivity survey, probably the least accurate of those discussed herein, has been described by Huddleston [103]. This consists in the use of the radio balance, an instrument originally intended for use in locating pipe lines or other buried metal. It consists of a six-tube, portable, impedence-coupled radio receiver and a two-tube oscillator. Both of these instruments are housed in wooden cases with built-in loops and batteries, and are mounted at the ends of the wooden rods, between which the operator walks. The apparatus operates on the principle that conducting materials act as a shield to the propagation of high-frequency waves. Consequently, the presence of conducting materials can be detected by properly designed apparatus. The instrument must be calibrated while holding it in succession over a number of soils of known resistivity. The deflection of the receiving set is proportional to the conductivity of the soil to a depth of about 4 feet. The test requires no excavations and gives a continuous reading. The apparatus is especially useful in approximately locating the boundaries of low-resistance soils, which are usually corrosive. Huddleston reports that 10 miles of right-of-way can be covered in a day by this method. The instrument weighs about 30 pounds.

(b) COLUMBIA ROD

The measurements discussed so far indicate only the resistivity of the soil. The currents that accompany corrosion depend not only on the resistivity of the soil but also on the potential of the metal with respect to the adjacent electrolyte and on the limitation of the corrosion currents by polarization films and corrosion products. Several attempts have been made to design soil-testing apparatus that would take account of one or more of these factors. One of them is the Columbia rod developed by Legg [104].

Figure 50 shows one form of the Columbia rod. It consists of a 1½-inch insulated rod tipped with a cone of steel, a few inches from

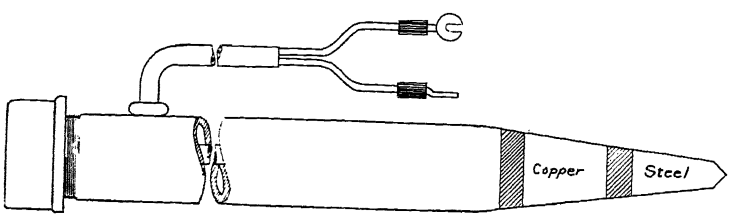

FIGURE 50.—*Columbia rod.*

which is an insulated ring of some more noble metal, such as copper. The two electrodes are connected to a sensitive milliammeter, which reads the current flowing when the two electrodes are in contact with the soil. The instrument is calibrated in terms of readings in soils of known corrosivity. The readings are affected by the quality of the contacts between the electrodes and the soil and is satisfactory only for some soil conditions. The changes in the current between the electrodes are indicative of film formation, and the amount flowing

depends on the effective areas of the electrodes as well as on other and more constant factors.

The apparatus could be made with the electrodes on separate rods, as in the Shepard apparatus, and an external battery could be used. This, however, would mask the galvanic effect and the polarization would depend on the applied voltage. The Columbia rod has not been fully developed and probably could be improved. It is not used extensively. Some tests indicate that the readings of the rod are affected chiefly by the resistance of the soil. The amount of soil involved in a single test is less than in a single test by the Shepard apparatus.

(c) REDOX APPARATUS

Soil corrosion in the eastern part of the United States, and perhaps elsewhere, is partly due to the depolarizing effects of anaerobic bacteria. The relation of these bacteria to corrosion is discussed elsewhere in this Circular. Starkey and Wight [105] have recently devised a means of determining whether or not a soil condition is favorable to the development of certain of these bacteria. The apparatus consists of two long insulated cylinders, one containing a glass electrode and a calomel electrode, by means of which the pH of the soil solution in a hole in the soil can be determined, and the other containing a platinum electrode and a calomel electrode for measuring the oxidation-reduction potential of the solution. From these measurements it is possible to determine whether or not the aeration and pH of the soil are favorable for the growth of some kinds of sulfate-reducing bacteria. A survey by means of the apparatus would probably indicate the corrosiveness of wet soils, such as swamps, marshes, and first bottoms of streams, but would not identify corrosive, well-aerated soils, except insofar as the corrosivity is indicated by the pH of the soil.

(d) IDENTIFICATION OF SOIL TYPES

The U. S. Department of Agriculture has examined and mapped by counties or similar subdivisions about two-thirds of the arable land of the United States, describing the characteristics of each soil horizon, usually to a depth of 6 feet. Each soil that differs chemically or physically from another is given a different name. Insofar as corrosion is dependent on soil characteristics, the name of the soil should indicate its corrosiveness if all the characteristics of the soil are known. However, the corrosiveness of only a few soil types or series has been investigated, and the corrosiveness of a soil series must usually be inferred from its chemical and physical characteristics in the absence of any experimental data. It may be possible, however, to recognize soil types described in Department of Agriculture publications and by associating unknown soils with known soils having similar descriptions, to form some idea as to their corrosiveness. Moreover, as in many regions the same soil types are recurrent, a soil survey along a right-of-way may be helpful in subdividing the territory with respect to its corrosivity. This is illustrated by the work of Denison and Ewing [40], who made a study of the repair records for 200 miles of pipe line right-of-way in Northern Ohio, which contained five parallel lines ranging in age from 26 to 44 years. Some of the physical characteristics of the soils traversed are shown in figure 51. In this study the number of repairs were taken as the measure of the corrosiveness of the soil. It will be shown later that some of the lines were repaired at the same place more than once. The repaired sections were usually given a protective coating

which presumably prolonged the serviceability of the pipe, and thus is equivalent to reducing the corrosivity of the soil. The length of the line repaired depended to some extent on the judgment of the operator. All these things interfere with correlating soil types with corrosion, as expressed in terms of reconditioning.

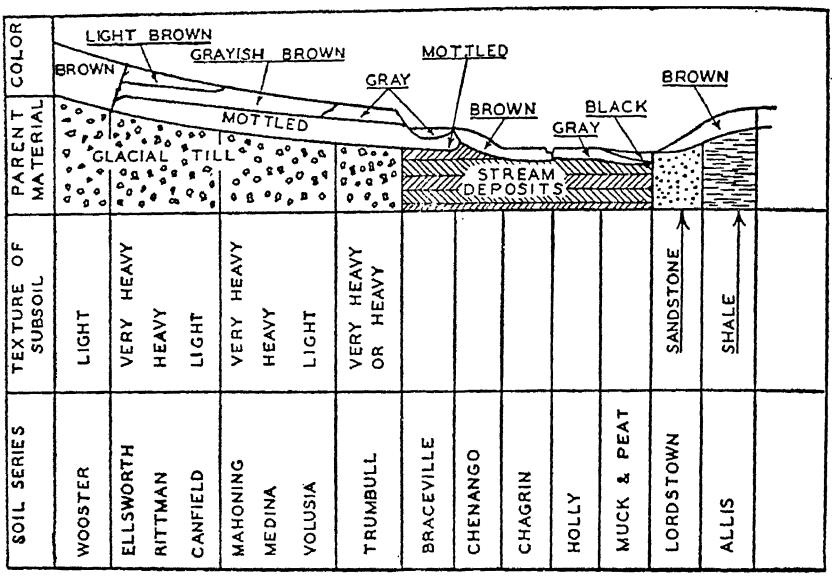

FIGURE 51.—*Characteristics of soils in the regions of glacial sandstones and shales.*

In table 90, in addition to the data on soil types and pipe repairs given therein, are reported the acidity and resistivity of the soil types so as to give some idea as to their homogeneity.

The significance of acidity and resistivity as measures of soil corrosivity is discussed in another section. It is apparent from the magnitude of the standard deviations of the mean and from the number of samples, that the average values given for the different soils are not equally reliable. Thus the average acidity and resistivity of an extensive soil type, such as Mahoning silt loam, was determined with a relatively high degree of precision because a large number of samples of such soils were taken. On the other hand, less reliance can be placed upon the values for soils present only to a limited extent along the pipe line as they are represented by so few samples.

It will be noted that for three soils, namely, the Clyde clay loam, the Brookston clay loam, and the Crosby silt loam, the data have been separated into two groups, for which, however, the respective acidities and resistivities are practically the same. This separation was suggested by the fact that the extent of repairs differs greatly in areas of each of these soil types, depending upon their position with respect to a certain division point on the pipe line. West of this division point, where the soils are more corrosive, the pipe lines closely parallel a railroad for many miles. It is possible that the accumulation of cinders on the surface of the soils might account for the greater corrosiveness in this region.

TABLE 90.—*Summary of data on soils and pipe-line repairs.*

Symbol	Soil: Symbol Type	Number of samples	Acidity (milliequivalent/100 g): Mean	Acidity: Standard deviation of mean	Resistivity (ohm-cm at 60° F): Mean	Resistivity: Standard deviation of mean	Length of line (in hundreds of feet)	Average percentage of pipe repaired	σ^x standard deviation of percentage of pipe repaired	Number of soil bodies
1	2	3	4	5	6	7	8	9	10	11
A1	Clyde clay loam, first section	13	14.6	1.5	2,758	224	2,180	46.2	22.3	30
A2	Clyde clay loam, second section	3	14.0	1.9	2,983	112	505	7.0	10.3	6
B	Braceville loam	2	15.0	.....	9,410	.....	164	23.3	15.1	4
Bc1	Brookston clay loam, first section	25	14.2	0.9	3,051	215	2,231	34.1	19.6	41
Bc2	Brookston clay loam, second section	7	14.0	2.7	2,965	600	3,101	18.4	19.3	15
C	Canaedea silt loam and fine sandy loam	8	12.7	2.1	4,329	837	1,324	13.3	11.0	19
Ca	Canfield silt loam	7	18.7	1.6	9,773	1,037	1,891	6.2	7.5	14
Ch	Chagrin silt loam and fine sandy loam	15	12.6	1.0	6,184	675	907	31.7	24.2	20
Ci	Cinders	6	14.6	4.0	2,081	160	562	59.6	25.0	7
Cs1	Crosby silt loam, first section	19	22.0	1.2	4,337	260	1,659	30.8	16.9	34
Cs2	Crosby silt loam, second loam	2	19.0	.....	5,660	.....	330	3.5	4.8	4
D	Chenango silt loam	2	9.5	.....	8,320	.....	317	19.6	28.3	9
E	Ellsworth silt loam	5	20.4	2.5	7,134	1,880	655	16.1	14.7	15
G	Genese silt loam	7	7.3	1.0	2,661	512	367	33.9	28.9	13
H	Holly clay loam	10	26.7	2.4	3,100	763	928	27.7	15.1	17
K	Lorain fine sandy loam	1	7.0	.....	4,400	.....	160	28.6	37.4	4
Kc	Lorain clay loam	5	14.0	3.2	3,489	321	745	7.1	5.9	8
L	Lordstown fine sandy loam	2	16.5	.....	11,450	.....	290	3.3	10.5	5
Ll	Millsdale and other shallow limestone soils	.....	.....	.....	.....	.....	680	11.1	2.7	3
Lf	Lucas fine and very fine sandy loams	2	6.7	.....	7,210	.....	184	0.0	.....	2
M	Mahoning silt loam	37	18.1	0.7	4,903	475	5,637	20.9	13.3	27
Ms	Miami clay loam, silt loam, and fine sandy loam	17	16.8	2.8	3,982	452	1,671	22.8	30.6	24
Mu	Muck	1	36+	.....	2,070	.....	134	39.4	16.2	3
N	Nappanee clay loam	3	17.5	3.6	1,009	350	535	57.0	.....	2
Nf	Newton fine sandy loam	1	8.0	.....	2,820	.....	207	6.5	10.7	6
P	Plainfield fine sand includes gravelly phase	2	6.7	.....	6,720	.....	1,160	3.1	5.1	19
S	Undifferentiated sands and sandy loams	1	8.0	.....	2,990	.....	3,555	4.0	4.2	9
T	Trumbull clay loam and silt loam	8	21.1	2.3	4,455	720	610	20.0	20.0	21
Ti	Till (some Allis and Chenango)	6	9.3	5.6	2,525	920	365	26.3	23.0	11
V	Volusia silt loam	30	17.2	1.0	5,473	383	4,105	13.6	14.2	35
Vl	Volusia loam	5	10.4	1.3	6,023	603	405	7.1	3.2	4
Wf	Wooster fine sandy loam	2	14.7	.....	6,442	2,718	278	12.4	8.2	4
Wl	Wooster loam	13	15.5	1.6	8,002	1,010	3,715	6.0	7.7	39
W	Wauseon fine sandy loam	2	7.5	.....	4,248	.....	240	6.3	.....	1
Wa	"Wauseon-like" soils	1	8.0	.....	694	.....	640	61.0	23.1	5

A summary of the data on soils and pipe line repairs is given in table 90. The repairs which have been made in the different soils are expressed as percentage of length per soil body. According to this method of expressing the data, the percentage of repairs (column 9) in the various bodies of a given soil type are simply averaged without regard to the size of the body. The standard deviation of the percentage of pipe repaired in each soil type (column 10) was obtained after weighting the percentages for each separate body according to the length of line in that body.

The data in table 90 show that, although there is considerable spread in the amount of pipe replaced in various areas of the same soil type, there are consistent differences in the corrosiveness of the various types. Thus among the most corrosive soils must be listed the Clyde clay loam first section (A_1), the soil overlaid by cinders (Ci), the Nappanee clay loam (N), and the "Wauseon-like" soils (Wa). On the other hand, the Canfield (Ca), Lordstown (L), and Wooster (Wl) loams, and the large group of undifferentiated sands and sandy loams (S) must certainly be considered as practically noncorrosive. The certainty with which the corrosiveness of the different soils is known depends upon the extent to which the soils occur along the pipe lines. For instance, relatively little weight can be given to the value for the Lorain fine sandy loam (L), since only one-half mile of this soil was mapped.

Table 90 also shows that the percentage of repairs in small bodies of a given soil type is more likely to differ from the average of that type than are the repairs in larger bodies. Errors in mapping the type boundaries and in locating the places where repairs were made in small bodies of soil introduce larger errors than in a single body of equal area.

The wide spread in the data summarized in table 90 may be illustrated by the repairs in a single soil type. In table 91 are shown the repairs in five bodies of the Lordstown sandy loam. It is easily seen that the repair of 570 feet in the 1,000-foot length of pipe line is inconsistent with the fact that only 380 feet of pipe were repaired in the remaining length of 28,000 feet. In this body where the pipe was repaired, which extended for 200 feet (5 lines), it would appear either that the soil is not really Lordstown sandy loam or the pipe did not require reconditioning solely on account of the corrosivity of the soil. Electrolysis or long line currents may have accelerated the corrosion.

TABLE 91.—*Repair data for Lordstown sandy loam.*

Total length of line	Length repaired	Length repaired
ft	*ft*	%
2,000	0	0
1,000	570	57
10,500	0	0
9,500	0	0
6,000	380	6.33
Total...29,000	950	3.27

The distribution of corroded areas as related to soil type is shown graphically in figure 52 for a typical section of the lines. Pertinent data such as the total and repaired lengths of line in each area and acidity and resistivity data are also shown. The marked differences in the corrosiveness of several soil types is immediately apparent. In the areas occupied by the Chenango silt loam (D) and the Holly clay loam (H),

it is seen that as many as three separate repairs have been made on short lengths of the lines. In contrast to these severely corrosive areas are intervening areas of Wooster loam (Wl) in which the repairs have been negligible. Similarly, it is seen that the area occupied by the Mahoning silt loam (M) is corrosive, but that few if any repairs have been made in the Canfield (Ca) and Ellsworth (E) silt loams and in the Volusia loam (Vl).

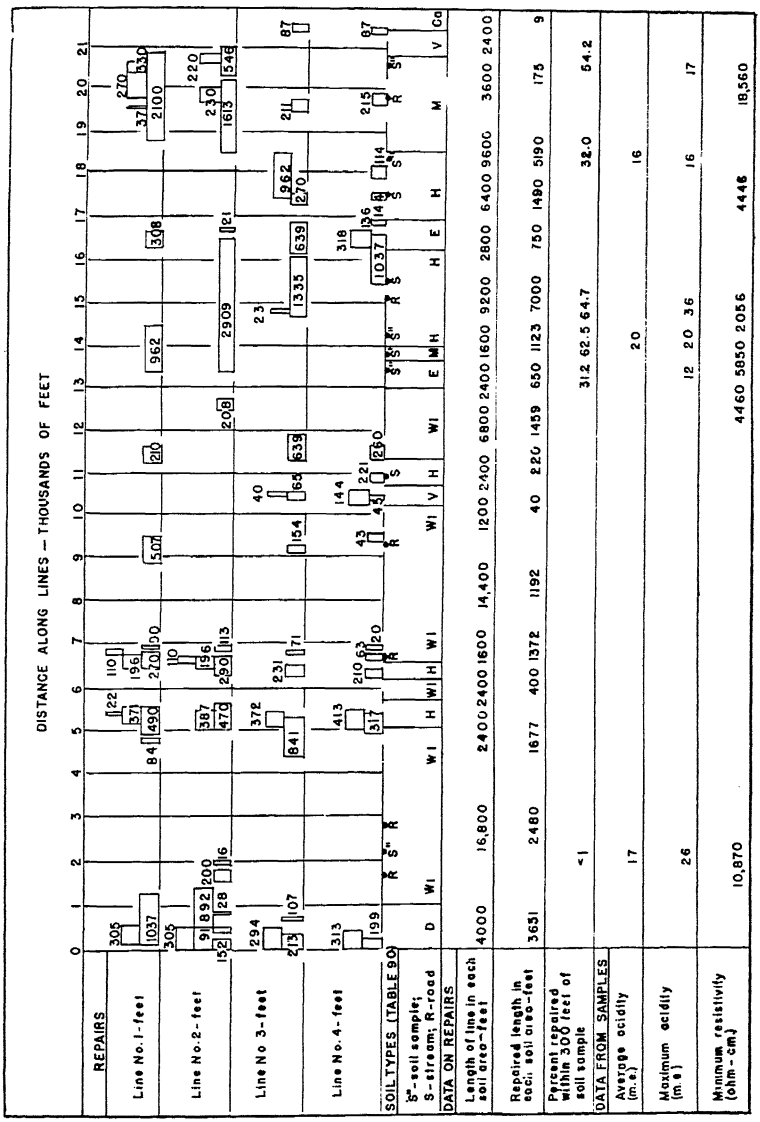

FIGURE 52.—*Repair and soil data for typical sections of pipe lines.*

Figure 52 further illustrates the errors, previously referred to, which may occur at the boundaries of the different soils. Thus it is seen that practically all the repairs that have been necessary in the area of

Wooster loam between 1,000 and 5,000 feet have been made at the boundaries of the adjacent soil types.

In considering further the relation between the various soils and their corrosiveness, it is of interest to compare the repairs made in certain soils with the degree of development of the horizons within the soil profile. In table 92, the typical upland soils of northeastern Ohio, which have developed from sandstone and shale, have been grouped in four vertical columns according to the degree of development shown by their profiles. Within each vertical column the soils are arranged according to the texture of the B-horizon. In table 93 a similar arrangement is shown for the glacial soils of northwestern Ohio, which have been derived from limestone.

TABLE 92.—*Relation between the degree of development of the glacial soils of northeastern Ohio and their corrosiveness.*

	Degree of development							
	1		2		3		4	
Color of surface soil	Gray		Gray brown		Light brown		Brown	
Mottling of A_1 horizon	Mottled		Mottled		No mottling		No mottling	
Mottling of B horizon	do		do		Mottled		do	
Mottling of C horizon	do		do		do		do	
	Series	Repairs	Series	Repairs	Series	Repairs	Series	Repairs
		Percent		*Percent*		*Percent*		*Percent*
Light B horizon	.....	.....	Volusia	13.6	Canfield	6.2	Wooster	6.0
Heavy B horizon	Trumbull	20.0	.....	.....	.....	.....	.....	.....
Very heavy B horizon	.....	.....	Mahoning	20.9	Ellsworth	16.1	.....	.....

TABLE 93.—*Relation between the degree of development of the glacial soils of northwestern Ohio and their corrosiveness.*

	Degree of development					
	1		2		3	
Color of surface soil	Grayish black		Dark gray		Gray brown	
Color of subsoil	Mottled bluish gray		Mottled bluish gray and yellowish brown		Mottled yellowish brown and yellowish gray	
	Series	Repairs	Series	Repairs	Series	Repairs
		Percent		*Percent*		*Percent*
Light B horizon	.....	.....	.....	.....	Miami	22.8
Heavy B horizon	Clyde	46.2	Brookston	34.1	Crosby	30.8
Very heavy B horizon	.....	.....	.....	.....	Nappanee	57.0

It is seen from the tables that the corrosiveness of the soils is related to their stage of development, the least developed soils being invariably the most corrosive. Thus the Trumbull soils, which are mottled throughout the profile and show very little differentiation into horizons, are seen to be corrosive, whereas the Wooster soils, which are well developed, are noncorrosive. It will also be observed that within the vertical col-

umns corrosiveness increases as the subsoil becomes heavier in texture.

The relationship between the stage of development and texture of the soils and their corrosiveness can be largely explained on the basis of their average acidity and resistivity. Because of the slight weathering that has occurred in the case of the poorly developed soils, such as those of the Trumbull series, there has been but little tendency for soluble materials to be removed, with the result that the average resistivity of these soils is relatively low. Similarily, the very heavy texture of poorly drained soils accounts largely for their high acidity, the acidity of a soil being a function of its content of colloidal material. Conversely, the high stage of development of the noncorrosive Wooster soils has resulted from the thorough removal of soluble salts, as indicated by their high average resistivity. Aside from the effects of acidity and resistivity, however, it is highly probable that those differences in the physical characteristics of the soils that determine their drainage and aeration have an important bearing on the observed relations.

The correlation of corrosion with soil types is helpful because the U. S. Department of Agriculture has mapped half of the soils of the United States, classified them as to soil type, and described each type. It might be possible, however, to make a simpler correlation by the use of soil series instead of soil types, as usually the different types in a soil series differ only in the texture of the uppermost layer, or A horizon. That is the subsoils are usually the same for most of the soils belonging to the same soil series. It is, therefore, of interest to examine the consistency of corrosion within the series, as it would be desirable, if possible, to take a soil series rather than a single soil type as a criterion for corrosion. To obtain data on this question, specimens of open-hearth iron, wrought iron, steel, and cast iron were buried in two or more soil types belonging to the same series but separated as to location. Unfortunately, some of the alkali soils that were selected were afterward found to differ in salt content. Table 94 shows the results of the tests. As the duration of the exposure in different soil types belonging to the same series differed somewhat, the corrosion losses and pit depths have been reduced to rates per square foot. The table is satisfactory for comparing materials in the same soil series, but should not be used for predicting corrosion for longer periods of exposure.

If allowance is made for the probable spread of data assignable to uncontrolled factors, it will be seen that corrosion within the soil series investigated is reasonably constant. An exception is the Norfolk series where the corrosion in Norfolk sandy loam is different from that in Norfolk sand. The subsoils of these two types are quite different. This serves as a warning that before assuming that corrosion throughout a soil series is the same, one should determine the sameness of the subsoils.

TABLE 94.—*Relation of soil series to rates of loss of weight and to weighted rates of maximum penetration of ferrous specimens.*

[Average of 2 specimens, except for the pit cast (A and L), the data for which cover 1 specimen only.]

Soil No.	Soil type	Location	Duration of test	Rates of loss in ounces, per square foot per year							Weighted rates of maximum penetration in mils per year						
				Open-hearth iron, A	Hand-puddled wrought iron, B, D	Bessemer steel, N	Southern cast iron, A or Z	Northern cast iron, L	Mono-cast centrifugal cast iron, I	Average for six specimens	Open-hearth iron, A	Hand-puddled wrought iron, B, D	Bessemer steel, N	Southern cast iron, A or Z	Northern cast iron, L	Mono-cast centrifugal cast iron, I	Average for six specimens
			Years														
101	Billings silt loam (low alkali).	Grand Junction, Colo.	9.27	1.13	1.01	0.99	1.10	1.18	0.87	1.05	13.7	9.7	8.8	12.3	20.6	14.8	13.3
102	Billings silt loam (moderate alkali).	....do	9.27	1.98	1.74	1.90	2.77	2.76	2.49	2.27	12.8	9.8	10.0	29.2	29.9	22.4	19.0
103	Billings silt loam (high alkali).	....do	9.27	2.02	2.30	1.92	6.33	4.57	4.88	3.67	19.1	13.9	19.9	43.4	36.6	20.5	25.6
	Average		.....	1.71	1.68	1.60	3.40	2.84	2.75	2.33	15.2	11.1	12.9	28.3	29.0	19.2	19.3
104	Cecil clay	Charlotte, N. C.	11.71	0.61	0.62	0.65	0.58	0.45	0.50	0.57	7.3	7.6	9.4	7.3	7.6	8.4	7.9
3	Cecil clay loam	Atlanta, Ga.	12.10	.35	.39	.36	.35	.32	.....	.35	5.0	5.3	5.7	12.1	9.9	.....	7.6
105	....do	Macon, Ga.	11.66	.41	.31	.42	.39	.39	.35	.38	4.7	4.1	4.4	8.8	11.6	9.3	7.2
106	....do	Salisbury, N. C.	11.70	.62	.74	.76	.68	.74	.66	.70	8.0	5.9	6.2	10.1	20.4	13.2	10.6
107	Cecil fine sandy loam	Raleigh, N. C.	11.70	.46	.47	.48	.27	.30	.30	.38	8.1	7.5	9.4	7.2	6.3	8.5	7.8
108	Cecil gravelly loam	Atlanta, Ga.	11.66	.41	.38	.50	.38	.47	.42	.43	6.6	5.9	7.6	17.9	20.2	12.8	11.8
	Average		.....	0.48	0.49	0.53	0.44	0.45	0.45	0.47	6.6	6.1	7.1	10.6	12.7	10.4	8.9
109	Fresno fine sandy loam (low alkali).	Fresno, Calif.	9.24	1.26	1.28	1.22	3.25	1.86	2.26	1.86	11.9	10.4	10.9	26.6	21.7	19.7	16.9
110	Fresno fine sandy loam (moderate alkali).	....do	9.24	2.01	1.71	2.19	1.94	1.84	2.08	1.96	14.7	12.5	16.0	22.9	25.1	25.7	19.5
111	Fresno fine sandy loam (high alkali).	Kernell, Calif.	8.90	1.98	2.12	2.18	3.00	2.57	2.74	2.43	[a] 17.1+	18.0	12.7	28.7	18.1	16.2	18.5
	Average		.....	1.75	1.70	1.86	2.73	2.09	2.36	2.08	14.6	13.6	13.2	26.1	21.6	20.5	18.3
112	Imperial clay (moderate alkali).	Niland, Calif.	5.93	3.34	2.85	3.17	4.13	5.28	[b] D	3.66	38.4+	26.5+	37.5+	45.4	43.4	46.4	39.6
113	Imperial clay (high alkali).	....do	5.93	4.34	3.68	3.98	D	4.82	[c] 5.75+	4.21	38.1+	29.2	38.1+	54.7	38.1	37.4	39.3
	Average		.....	3.84	3.27	3.58	.....	5.05	.....	3.94	38.3	27.9	37.8	50.1	40.8	41.9	39.5

22	Memphis silt loam	Memphis, Tenn.	11.65	0.60	0.68	0.67	.....	0.72	.....	0.67	4.6	4.8	5.4	.....	13.4	.....	7.1
115	....do	Vicksburg, Miss.	11.69	.28	.30	.33	0.20	.20	0.17	.28	6.7	4.1	5.4	9.6	7.0	6.3	5.8
	Average		.....	0.44	0.49	0.50	.....	0.46	.....	0.47	5.7	4.5	5.4	.....	10.2	.....	6.5
23	Merced silt loam	Buttonwillow, Calif.	10.18	1.94	1.94	2.13	6.11	2.78	.....	2.98	14.7	13.1	13.1	31.5	20.7	.....	18.6
116	Merced clay	Los Banos, Calif.	9.27	2.33	2.06	2.10	4.74	4.00	3.59	3.05	12.8	17.2	9.4	28.9	23.1	22.1	18.3
117	Merced clay loam adobe	Tranquillity, Calif.	9.27	2.26	2.14	2.24	1.90	2.29	1.64	2.16	19.1	13.2	14.8	17.7	17.3	15.9	16.4
	Average		.....	2.18	2.05	2.15	4.25	3.02	.....	2.73	15.5	14.5	12.4	26.0	20.4	.....	17.8
119	Norfolk sandy loam	Macon, Ga.	11.66	0.70	0.75	0.76	0.50	0.60	0.50	0.66	8.2	5.7	6.2	12.2	11.8	8.4	8.8
120	Norfolk sand	Pensacola, Fla.	11.65	.16	.15	.18	.066	.037	.092	.12	2.9	2.3	2.1	2.6	1.5	3.9	2.3
121	....do	Tampa, Fla.	11.71	.12	.12	.13	.028	.014	.10	.082	2.2	2.0	1.7	1.8	2.2	4.4	2.0
31	Norfolk fine sand	Jacksonville, Fla.	12.04	.24	.23	.23	.31	.19	.....	.24	3.2	3.1	3.0	5.2	1.5	.....	3.2
	Average		.....	0.31	0.31	0.33	0.23	0.21	.....	0.28	4.1	3.3	3.3	5.5	4.3	.....	4.1
42	Susquehanna clay	Meridian, Miss.	12.03	0.93	0.74	0.92	2.53	1.18	.....	1.32	10.3	6.7	7.2	22.8	16.0	.....	12.6
123	....do	Shreveport, La.	11.68	.89	.94	.94	0.75	0.83	0.85	0.87	3.8	4.9	5.1	18.0	15.4	11.0	9.4
124	Susquehanna silt loam	Troup, Tex.	10.50	.71	.74	.74	.54	.63	.58	.67	6.6	6.7	6.6	5.0	6.6	11.0	6.3
125	Susquehanna fine sandy loam.	Shreveport, La.	11.85	.59	.67	.72	.71	.72	.84	.69	5.5	5.7	6.1	7.3	7.3	7.8	6.4
	Average		.....	0.78	0.77	0.83	1.14	0.93	.....	0.89	6.6	6.0	6.3	13.3	11.3	.....	8.7
12	Hanford fine sandy loam	Los Angeles, Calif.	6.17	.45	.51	.44	0.37	0.35	.....	0.45	9.0	10.4	9.8	9.3	3.5	.....	9.6
13	Hanford very fine sandy loam.	Bakersfield, Calif.	5.89	1.04	.91	1.33	2.16	.....	.....	1.37	8.0	9.6	8.1	30.0	.....	.....	14.0
	Average		.....	0.75	0.74	0.89	1.27	.....	.....	0.91	8.5	10.0	9.1	19.7	.....	.....	11.8
25	Miami clay loam	Milwaukee, Wis.	16.99	0.19	0.16	0.16	0.15	0.14	.....	0.16	3.2	3.0	3.1	5.7	5.8	.....	4.2
26	Miami silt loam	Springfield, Ohio	16.93	.24	.28	.28	.23	.19	.....	.24	3.4	2.4	3.2	8.2	4.5	.....	4.3
	Average		.....	0.22	0.22	0.22	0.19	0.17	.....	0.20	3.3	2.7	3.2	7.0	5.2	.....	4.3

[a] + indicates 1 or more punctures due to corrosion.
[b] D = Destroyed by corrosion.
[c] Data for 1 specimen only. The other was destroyed by corrosion.

3. LABORATORY TESTS

(a) RESISTIVITY

The conductance of most soil is almost entirely electrolytic. The resistance of a soil, therefore, depends on the moisture in the soil, the salts in solution, the distribution of the moisture, and its temperature. The compactness of the soil affects its resistance, and in a measurement of a small volume of soil containing stones or gravel, the result may be affected by the distribution of this inert material. If direct current is used, the results may be affected by polarization and endosmose. The National Bureau of Standards [106] made a rather extensive study of soil resistivity in the course of its study of stray-current electrolysis, and for several years made soil-resistivity measurements on samples of soil. These, as received from the field, were placed in a glass-lined cylinder having a volume of about 800 milliliters and provided with a movable piston by which the sample was subjected to a pressure of 50 pounds per square inch. Measurements were made with a voltmeter and ammeter, using 60-cycle current. At 50-pound-per-square-inch pressure, the resistivity of most soils was found to be about that of the undisturbed soils.

Although such measurements may have shown the resistivity of the soil at the time the sample was taken, the results were questionable because another sample taken at a different time might have a very different resistivity because of a different moisture content. Later soil-resistivity measurements were made with the soil sample saturated, using a Wheatstone bridge and a 1,000-cycle current. From the resistance, the resistivity at 60°C was calculated. The volume of soil tested was 46 milliliters. From the standpoint of the soil scientist, the change in method had several advantages, although the results were in many cases not representative of the resistivity of the soil in the field at any time, and the chances of the sample being representative decreased with the decrease in the volume of the sample tested. As the resistivity of the soil in the field may vary considerably from point to point and from time to time, and as resistivity is only one of the characteristics which influence its corrosivity, an approximate value is sufficient for most purposes.

Another container used at the Bureau consists of a Bakelite frame with removable iron electrodes at the ends and having a cross section of 5 square centimeters and a length between electrodes of 5 centimeters. The resistivity of soil in this frame is equivalent to its resistance. Another frame was constructed having a cross section of 30 square centimeters and an inside length of 3 centimeters, so that the resistivity of the soil equaled 10 times the observed resistance. These containers were placed on glass plates, and measurements were made with the alternating current bridge. Wahlquist [101], for some of his field measurements, used a wooden box lined with waxed paper. The box had a length of about 8 inches and a cross section of about 4 square inches. Current terminals were placed at the ends of the box, and point potential terminals were so spaced near the center that the resistivity of the soil equaled the resistance, which was measured by means of a battery, milliammeter, and vacuum-tube voltmeter. The separation of the current and potential electrodes avoids the inclusion of polarization effects at the current terminals. However, the voltmeter terminals may differ somewhat in potential. This source of error may be avoided by applying different currents and dividing the change in voltage by the change in current. When the measurement has been completed, the soil is slipped

out of the box and wrapped in the waxed paper for later reference. The effect of compacting the soil in a test box is shown in figure 53.

The effect of the moisture content on the resistivity of a clay soil is shown in figure 54. Other kinds of soils would yield different curves because of their different salt content and moisture equivalent, as is shown in tables 20 and 21. The effect of temperature on the resistance of one soil is shown in figure 55. For temperatures between 0° and 25°C the relation between soil resistance and temperature is given by the equation $R_{15.5}=R_t(24.5+t)/40$, in which $R_{15.5}$ is the resistance at 15.5°C (60°F) and R_t is the resistance at the temperature t °C.

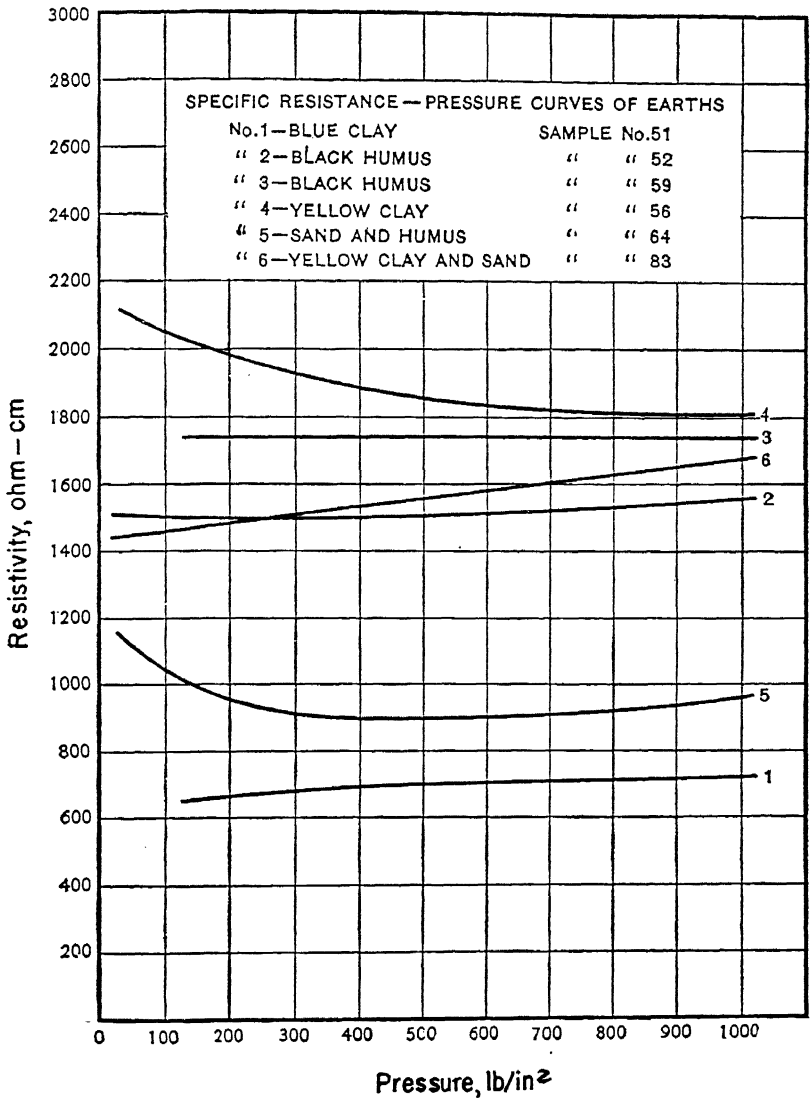

FIGURE 53.—*Specific resistivity of soil at different pressures.*

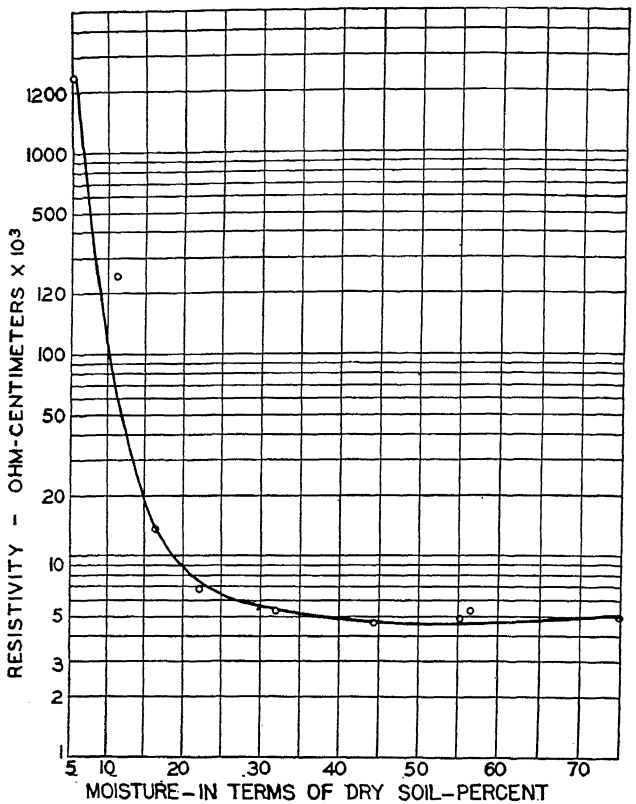

FIGURE 54.—*Effect of moisture content on soil resistivity.*

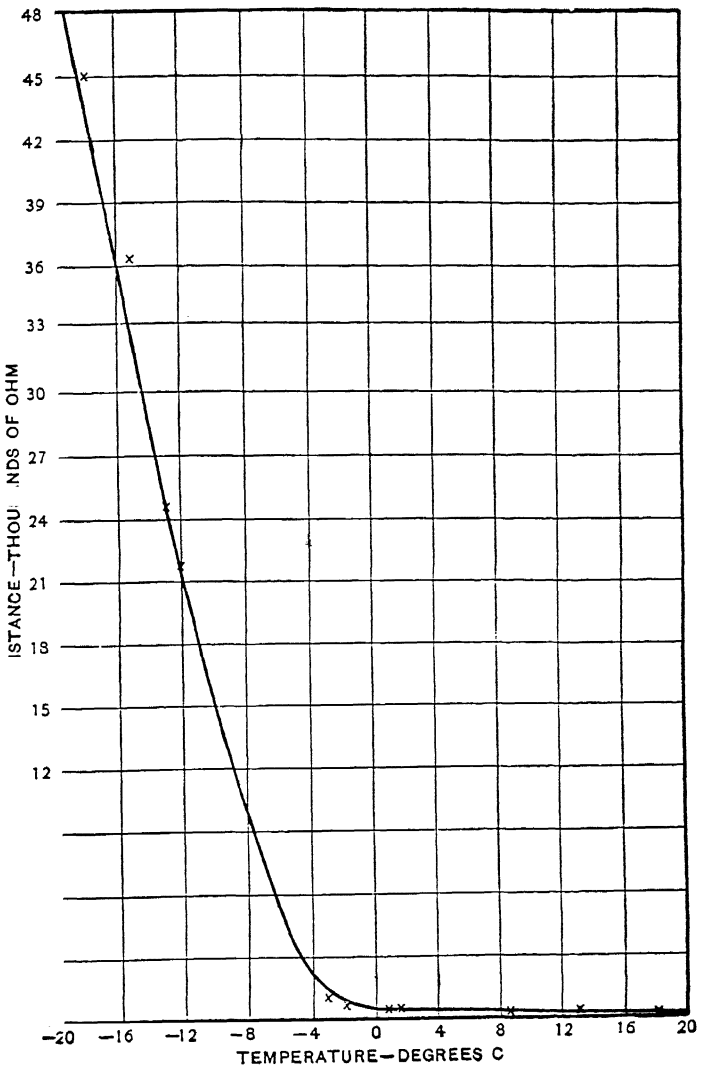

FIGURE 55.—*Effect of temperature on earth resistance.*

(b) HYDROGEN-ION CONCENTRATION AND TOTAL ACIDITY

Holler [107], as a result of a study of hydrogen evolution from iron filings in contact with soil in the absence of oxygen, found a logarithmic relation between the total acidity of the soils at the Bureau test sites and the volume of hydrogen evolved and suggested that the corrosiveness of soils in humid regions might be predicted from their acidity. Because of the very slight dissociation of the soil acids, the pH value of a soil may offer no indication of the capacity of the acidic material to prevent the formation of a protective layer of hydroxides that tends to form as a result of initial corrosion. It has been noted that with a definite oxygen concentration the rate of corrosion is determined by the total quantity of ionizable hydrogen that comes into contact with the metal surface, rather than by the hydrogen-ion concentration of the corrosive medium. Unless the quantity of acid that comes into contact with the metal surface is sufficient to prevent the formation of protective hydroxide films, these films will tend to form regardless of the H-ion concentration. In order to determine the effect of soil acidity on corrosion in aerated soil, Denison and Hobbs [39] made up a series of synthetic soils differing chiefly in total acidity. They found that, under the conditions of their test, the rate of corrosion was roughly proportional to the total acidity of their soils. A somewhat less definite relation was found between the rate of pitting and the acidity of soils from Bureau test sites.

The determination of total acidity of soils is somewhat difficult because of the slight solubility of soil acids. The details of the procedure followed in determining acidity by the "difference" method as described by Denison [108] are as follows. The capacity (T) of the soil to absorb exchangeable bases was first determined. A 25-gram sample of soil was placed in a 250-milliliter Erlenmeyer flask with about 1 gram of calcium carbonate added. The soil was treated with 150 to 200 milliliters of 1 N NaCl that had been heated to 80° to 90° C. The mixture was maintained near that temperature for 1 hour, with occasional shaking. The mixture was then poured into a 400-milliliter bottle and shaken overnight in an end-over-end shaker and also for 2-hour periods on 2 succeeding days. After standing another night the extract was decanted and filtered into a 1-liter beaker. Then 200 milliliters of salt solution was added to the soil. The mixture was shaken 1 hour, allowed to settle, and the extract then decanted through the filter as before. This process was repeated until 1 liter of extract was obtained. For the final filtration, the entire quantity of soil was poured on the filter and washed. The extract was then mixed thoroughly, and the calcium in a 400-milliliter portion was determined gravimetrically. From the value thus obtained, the quantity of calcium equivalent to the solubility of calcium carbonate in 1 liter of 1 N NaCl was subtracted.

The quantity (S) of replaceable calcium in the soil was determined in a manner similar to the determination of the exchangeable base capacity, except that no calcium carbonate was added and the shaking was limited to 18 hours. For those soils in which calcium carbonate occurred naturally, a correction was made for the calcium that had been dissolved as carbonate by the salt solution. This quantity was calculated from the amount of bicarbonate in solution, which was estimated by titrating an aliquot portion of the extract with standard acid to the color change of methyl orange. The quantity ($T-S$) of exchangeable hydrogen or the total acidity of the soil was obtained by

subtracting from the exchange capacity of the soil the absorbed calcium found to be present.

Ewing [109] devised a shorter method that duplicates the results of Denison's method within about 15 milligram equivalents per 100 grams of soil. Ewing's method is as follows: Two 5-gram portions of the air-dry soil, previously pulverized and passed through a 20-mesh (per linear inch) sieve, are placed in two 25- by 200-millimeter test tubes, and then 25 milliliters of normal NaCl solution is added to each tube. One milliliter of 0.2 N Na_2CO_3 solution is pipetted into one tube and 2 milliliters into the other. (One milliliter is equivalent to 4 milliequivalents of acid per 100 grams of soil for the 5-g sample.) The pH of the more alkaline solution is then determined. If the pH is found to be below 8, 2 milliliters more of the carbonate solution is added to each tube and the process repeated until the pH of the more alkaline solution is above 8. The tubes are allowed to stand, with occasional shaking, until the solutions are in equilibrium with the soil and show no further changes of pH with time. The pH of the solution in each tube is then determined. Usually the resulting pH values are so near to pH 8 that by interpolation or extrapolation the amount of alkali required to bring the soil to pH 8 can be determined. For example, if 12 milliequivalents (3 ml) of the carbonate solution give a pH of 7.7 when in equilibrium with the soil and 16 milliequivalents (4 ml) give a pH of 8.1, the acidity of the soil will be 15 milliequivalents per 100 grams. The titration curve is assumed to be a straight line through the range of interpolation and extrapolation.

TABLE 95.—*Repairs in soil types as related to total acidity.*
[Resistivity 4,000 to 5,000 ohm-centimeters]

Soil type	Total acidity (mg-eq/100 g soil)	Pipe line repaired
	mg-eq	*Percent*
Wauseon fine sandy loam	7.5	6.3
Caneada silt loam [a]	12.7	13.3
Miami silt loam [b]	16.8	22.8
Mahoning silt loam	18.1	20.9
Trumbull clay loam [c]	21.1	20.0
Crosby silt loam, first section	22.0	30.8

[a] Includes fine sandy loam.
[b] Includes clay loam and fine sandy loam.
[c] Includes silt loam.

The relation of the total acidity of the soil to its corrosivity is indicated by table 95. Of course, the corrosivity of most soils is influenced by several of their characteristics, some of which are not closely related. Consequently, in many cases there is no close correlation between a single soil characteristic and corrosion. For the northern Ohio soils previously discussed, Denison and Ewing found that the corrosivity could be roughly expressed by the equation $P=7500(A-5)/R$, in which P is the percentage of pipe repaired, A is the total acidity in mil equivalents of hydrogen per 100 cubic centimeters of soil, and R is the soil resistivity in ohm-centimeters. Although the relation between hydrogen-ion concentration and total acidity that has been discussed affords a sufficient explanation for a lack of correlation between hydrogen-ion concentration and corrosion, several factors that affect the determination of pH values at the National Bureau of Standards and elsewhere may also have affected the results. One of these was the use of a colorimetric method for pH determinations, which in most cases necessitated the addition of water to the soil.

The difficulty of obtaining a clear soil solution or of matching colors when the solution was not clear sometimes may have resulted in inaccurate determinations. More important, probably, is the fact discovered by Romanoff [47] that if certain soils are air-dried prior to the determination of their hydrogen-ion concentrations, as is the practice of the Department of Agriculture and the National Bureau of Standards, the pH values undergo changes due, probably to the oxidation of sulfides in the soils. The total acidity of the soil may change also. It is possible, therefore, that in some cases the pH values used in the correlation of pH values and corrosion were incorrect. The changes referred to occur in some poorly aerated soils containing active sulfate-reducing bacteria. The hydrogen-ion concentrations of other poorly aerated soils are unaffected by aeration. When conditions permit, the pH values of the soils at the National Bureau of Standards test sites will be redetermined without exposing them to the air, but it seems probable that only a few changes in the published values will be necessary.

(c) PUTNAM'S DECOMPOSITION POTENTIAL TESTS

A test that has been used extensively in the West is one devised by Putnam. This test has undergone several changes with respect to apparatus and the way in which the data are treated. The original test [110] was one of the earliest attempts to determine soil corrosivity and to associate corrosion with the electrical condition of the corroding metal.

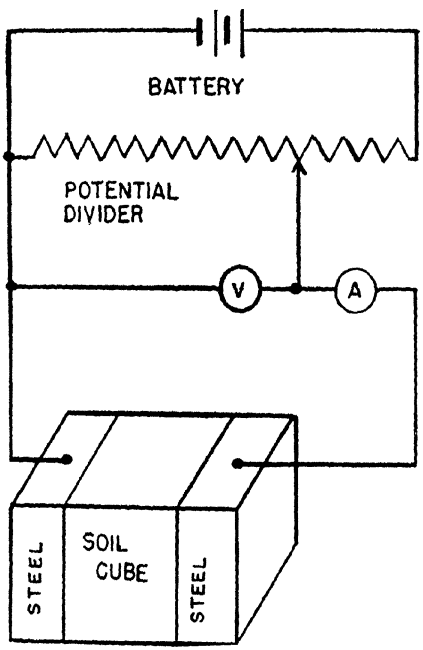

FIGURE 56.—*Putnam apparatus for testing for potential corrosivity.*

The latest modification [52] takes account of the resistivity and acidity of the soil and of polarization. There are some, however, who doubt the validity of the theory upon which the test is founded.

The test involves the determination of the resistivity and pH of the

soil and the value of current under certain experimental conditions which Putnam calls the "potential corrosivity" of the soil. The circuit for determining potential corrosivity is shown in figure 56. Two polished-steel electrodes having faces 1 inch square are held in a bakelite case (not shown) with their faces 1 inch apart to form cubical cell 1 inch on a side. The soil under test is compacted in this cell under a pressure of 500 pounds per square inch. The resistance of the soil cube is determined by measuring the resistance between the electrodes with an alternating-current Wheatstone bridge. A potential difference of 1.4 volts (causation potential, E_c) is then impressed between the steel electrodes by means of a battery and potential divider as shown. After the current has reached a practically steady value, usually after about 5 minutes, its value, C, is read. The equation $C=(1.4-Ed)/R$ gives the value of the current in terms of the causation potential (1.4 volts), the decomposition potential, Ed, and the resistance, R, of the soil cube. The value of C in milliamperes is called the potential corrosivity. Values of pH are determined colorimetrically in a neutral 5-percent potassium chloride solution. By correlating these values with the National Bureau of Standards soil-corrosion data, Putnam derived several empirical relationships for determining such quantities as the loss per square foot, the average maximum pit depths, and the total number of leaks per mile in a given time.

(d) WILLIAMS-CORFIELD OR NIPPLE-AND-CAN TEST

A more frequently used and simpler test, which, however, has less theoretical background than Putnam's, is the Williams-Corfield [54], or nipple-and-can, test. Its chief claim for consideration is that the corrosion index obtained by its use has been correlated with a large amount of corrosion experience. A 4-inch length of ¾-inch sand-blasted iron pipe is carefully weighed, and a rubber stopper is inserted in one end so that it protrudes one-half inch. It is then placed in the center of a pint friction-top tin can, with the stopper resting on the bottom, and the remaining space is filled with a water-saturated sample of the soil to be tested. The pipe is connected to the positive side of a 6-volt storage battery, and the other side of the battery is connected to the can. Several tests are usually run in parallel. Corfield uses a clock to disconnect the battery after 24 hours. The pipe is removed, cleaned, and reweighed. The loss of weight in grams is the corrosion index. Soils are grouped as to corrosivity as shown in table 96.

TABLE 96.—*Corfield corrosivity index.*

Corrosion index	Corrosiveness
3 grams and over	Very bad
2 to 2.99 grams	Bad
1 to 1.99 grams	Fair
Less than 1 gram	Good

Figure 57 shows Corfield's apparatus. Corfield tested about 8,000 samples of soil from Los Angeles, Calif. and vicinity by this method to make a soil-corrosivity map of the territory under his supervision. The method has been used extensively by others and appears to be reasonably satisfactory for soils such as occur in California. There are few checks on the reliability of the method when applied to the acid soils of the East.

Among objections to the test are (1) the applied voltage is much greater than those occurring in soil corrosion, and (2) the loss of weight is caused by and is proportional to the current which flows. The current is controlled by the resistance of the soil and by polarization, which in turn is a function of the current. However, Corfield has shown that the same sort of data are obtained when a two-volt battery is used, and the decrease in current due to polarization seems to be a characteristic of the soil. The advantages of the test are ease of manipulation, speed (as many tests can be run in parallel), and the extensive correlation that has been made with field experience.

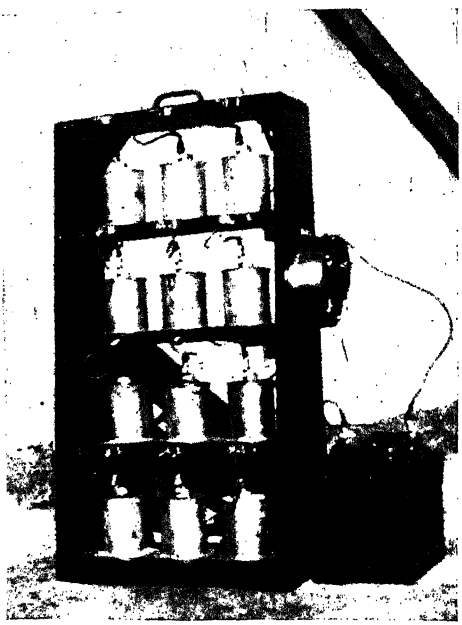

FIGURE 57.—*Corfield apparatus.*

(e) DENISON CELL TEST

Denison's cell test, described on page 181, was devised primarily for studying the general phenomena of corrosion but has been used to a limited extent to determine the relative corrosivities of different soils. The test more nearly simulates actual soil conditions than the tests so far discussed and yields more reproducible results. On the other hand, it requires greater care, more apparatus and more time than the other tests.

4. VALUE OF SOIL-CORROSIVITY TESTS

Experienced pipe-line operators can often identify a considerable percentage of the corrosive-soil conditions in a given area, such as swamps, alkali knolls, adobe soils, or alkaline soils without tests. The question is often raised, therefore, as to whether or not the various tests that have been developed for determining the corrosivity of soils are capable of reliably identifying a sufficiently greater percentage of corrosive conditions to warrant their use. Another important question is the relative

value of the different tests. At first thought, it might appear to be a simple matter to answer these questions by comparing the results of laboratory or field tests on individual soils with the amount of corrosion observed on pipes laid in the same soils. As a matter of fact, however, the problem is not so simple. The results of such a comparison will depend to a certain extent upon what criterion is adopted for judging the amount of corrosion. Maximum pit depths, leaks per unit length, number of replacements, or estimated condition of the pipe are the principal criteria that have been used for this purpose. The element of time must also be taken into account because corrosion does not, as a rule, proceed at a uniform rate, and the pipe may not have the same wall thickness in different parts of the line. Also, the relative corrosiveness of various soils is not the same for coated pipe or with respect to their destructive effect on various coatings as it is with respect to bare pipe. In general, it can be said that each of the different tests can identify certain corrosive conditions in the soil but that no single test can identify all places where corrosion is likely to occur. Also it is probable that their relative effectiveness will differ in different localities. Thus, tests of acidity are useless in alkaline soils. Resistivity tests are not very effective if the resistivity is high, and Denison found it advisable to modify his method when testing muck and similar wet soils. These facts should be kept in mind in considering the following comparisons reported in 1939 by Logan and Koenig [111].

In 1937 the Magnolia Pipe Line Co. uncovered approximately 25 miles of 8-inch asphalt-coated steel line in southeastern Texas, measured the depths of the deepest three pits on each joint of pipe, and estimated the condition of each joint. The soils along the right-of-way were mapped according to the methods of the United States Department of Agriculture. 250 soil samples were taken at pipe depth, parts of which were sent to the National Bureau of Standards for test. The resistivity of the soil was determined at 200-feet intervals by means of the Shepard resistivity apparatus. At the National Bureau of Standards, the hydrogen-ion concentration, total acidity, alternating-current and resistivity at saturation were determined for each sample. The small size of the samples made it impossible to run the Corfield test with full-size apparatus but small-scale apparatus was used that produced the same current densities as the larger apparatus.

The Columbia rod test was simulated by placing soil in a cell having a copper and a steel electrode. A milliammeter was used to measure the current developed. The Putnam test was simulated insofar as determination of the potential corrosivity, that is, the current furnished by the cell, was concerned, but this potential corrosivity was not reduced to equivalent pit depths by means of Putnam's curves and equation. Therefore, the data do not indicate the reliability of the Putnam test, as described above. The Denison test was also run according to the practice of Denison at that time.

An examination of the data on the pipe indicated that there was a fairly close relationship between the estimated condition of the pipe, the number of punctures, the depth of the deepest three pits, and the depth of the deepest pit on a joint of pipe. For convenience, the depth of the deepest pit was taken as the criterion of corrosion. The data for the various soil corrosivity tests were correlated with the condition of the pipe as indicated by this criterion.

(a) CORRELATION OF SOIL TYPES WITH PIT DEPTHS

Figure 58 shows the extent to which the soil series and types were indicative of soil corrosivity. The cross hatched columns represent the averages of all the maximum pit depths in the soil series. The number of observations, the standard deviations of the data, and standard errors of the averages are shown. Most soil series were represented by two or more soil types which are represented by the open columns. Thus the figure shows the variations in the corrosiveness of the soil types within the series.

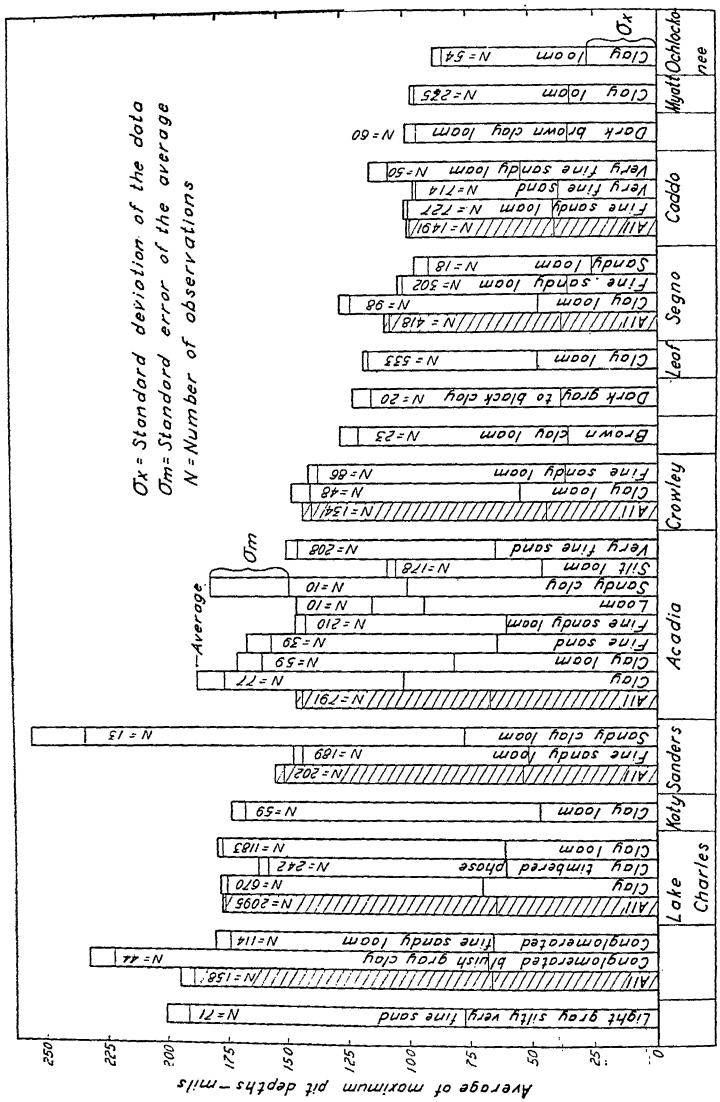

FIGURE 58.—*Maximum pit depths on sections of pipe exposed to different types of soils.*

The standard deviations show how widely the individual pit depths differed. As has been noted, the several soil types of a series usually do not differ greatly in corrosiveness. Figure 58 shows that some soil series are definitely more corrosive than others. The differences shown

are those for soils within 25 miles of each other and do not represent the differences between soils in different parts of the country.

Figure 59 shows the pit depths on sections of pipe adjacent to the spot where the soil was sampled to identify its type. It will be seen that the averages of the pit depths on the pipes in the different soils differ widely and that some soil types are much more corrosive than others. However, the range in pit depths in any one soil type is very great. This should make it evident that the examination of a single joint of pipe in a soil type is likely to give a very misleading idea of the corrosiveness of that type of soil. A large number of observations are necessary for the determination of the corrosiveness of a soil type or the condition of the pipe line in even a single type of soil.

The descriptions of the soil textures near the top of the figure 59 refer to the textures of the soil samples taken at pipe depth. It will be noted that these textures of the soil at pipe depth differ from those given below in the name of the soil type. This is because the latter refer to the textures of the A horizons. The stars indicate the maximum pit depth on the pipe nearest the soil sample for which the texture was determined.

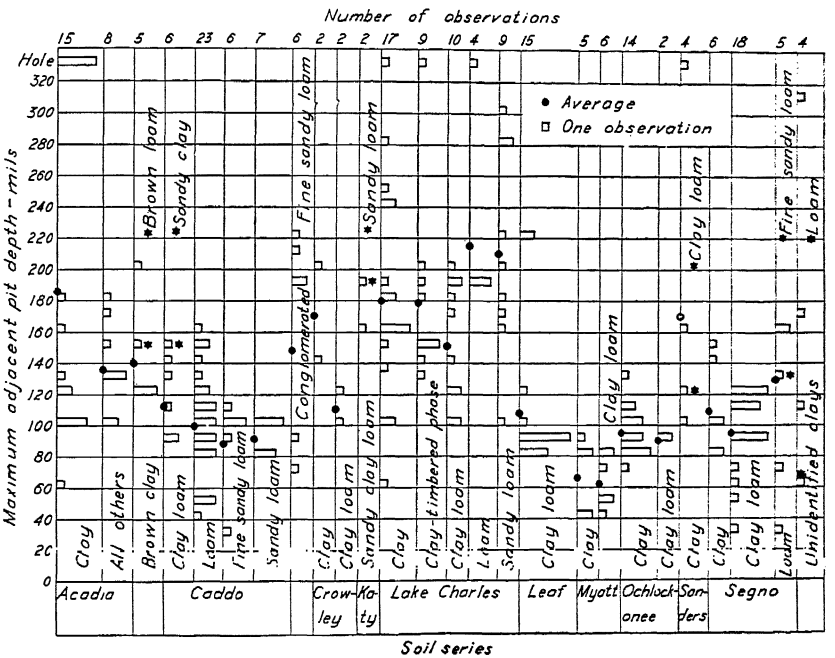

FIGURE 59.—*Maximum pit depths on sections of pipe adjacent to places at which soil samples were taken.*

(b) CORRELATION OF CORROSION WITH FIELD RESISTIVITY

(1) *Shepard's Soil-Resistivity Measurements.*—Measurements of soil resistivity in the field were made at intervals of 200 feet, by means of Shepard's apparatus. These measurements might be taken as representative of soil conditions along ten 20-foot lengths of pipe, and on this assumption the resistivity of the soil should be compared with the average of the maximum pit depths on the 10 sections of pipe nearest the sampling point, as is done in figure 60. The range of pit depths

for each value of soil resistivity is so great that it might be thought that the soil sample did not represent soil conditions to which all of the 10 lengths of pipe were exposed. Consequently, a correlation was made between the resistivity of each soil sample and the depth of the deepest pit on the joint of pipe nearest the sample. The result is shown in figure 61. The correlation is no better than that in figure 60. Each figure shows that the average maximum pit depth tends to decrease as

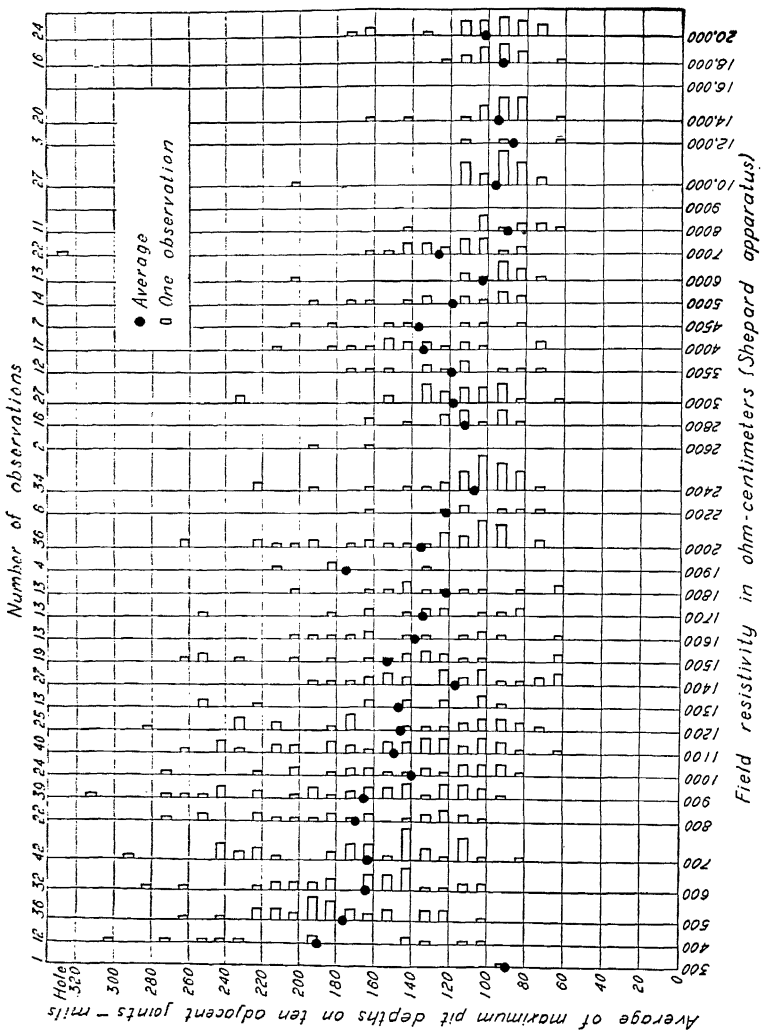

FIGURE 60.—*Relation between soil resistivity measured in the field and the average of the depths of the deepest pits on the 10 sections of pipe nearest the place at which the resistivity was measured.*

the resistivity of the soil increases, but that there is a wide range of pit depths associated with each value of resistivity. Evidently other factors affect the pit depths.

It might be thought that the poor correlation between pit depths and soil resistivity is obtained because pit depths are not indicative of the corrosivity of the soil. Many pipe line operators divide their used pipe into classes, or conditions, based on the amount of work

required to recondition it. One of these classifications is as follows: Condition 1, no pits deeper than 120 mils, no repairs required; condition 2, pit depths ranging between 70 and 260 mils, not more than 25 spot welds required; condition 3, numerous pits but generally not deeper than 40 mils and not more than three punctures; condition 4, junk.

The pipe on which pit depths were measured was classified on this basis and figure 62 constructed. It is very similar to figure 61 and

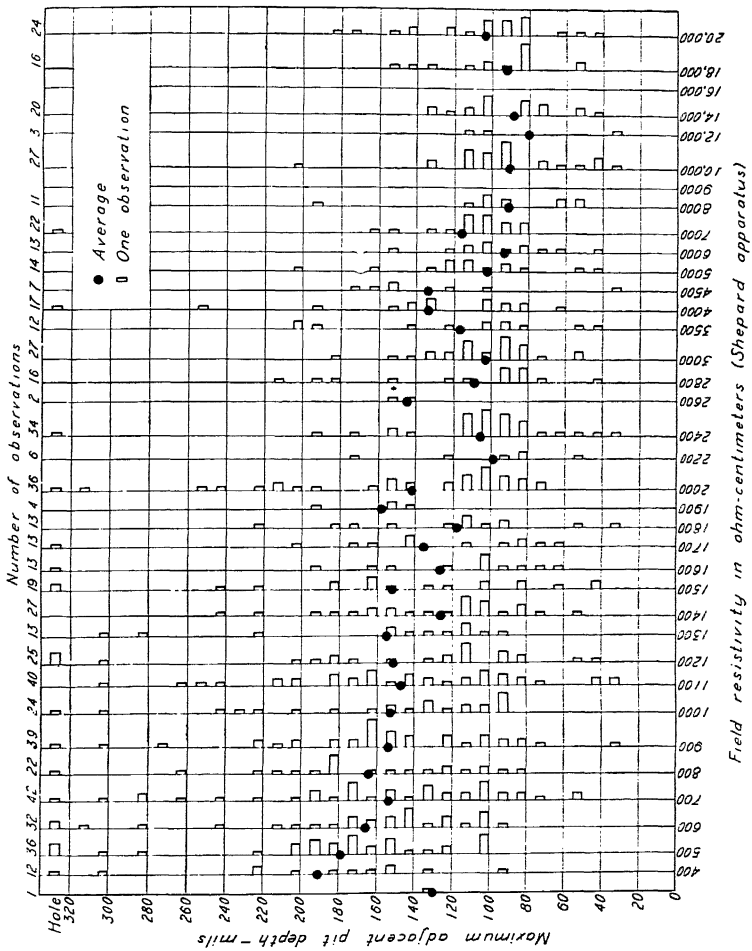

FIGURE 61.—*Relation between the field resistivity of the soil and the maximum pit depth on t. section of pipe nearest the place at which the soil resistivity was measured.*

indicates that the two criteria for soil corrosivity, namely, maximum pit depths and pipe conditions, are equally good. Figure 63 presents another way of studying the relation of soil resistivity to the condition of the pipe. The ordinate on the left indicates the number of lengths of pipe in each condition and enables one to study the relation between individual pipe condition and soil resistivity. The right-hand ordinate applies to the average of the pipe conditions (dots) for each resistivity. This curve shows little relationship between pipe condition and soil resistivity. Since the condition of the pipe was based on the judgment

of one or more inspectors and not on measurements, it is not surprising that the assigned condition of the pipe does not accurately represent the corrosivity of the soil.

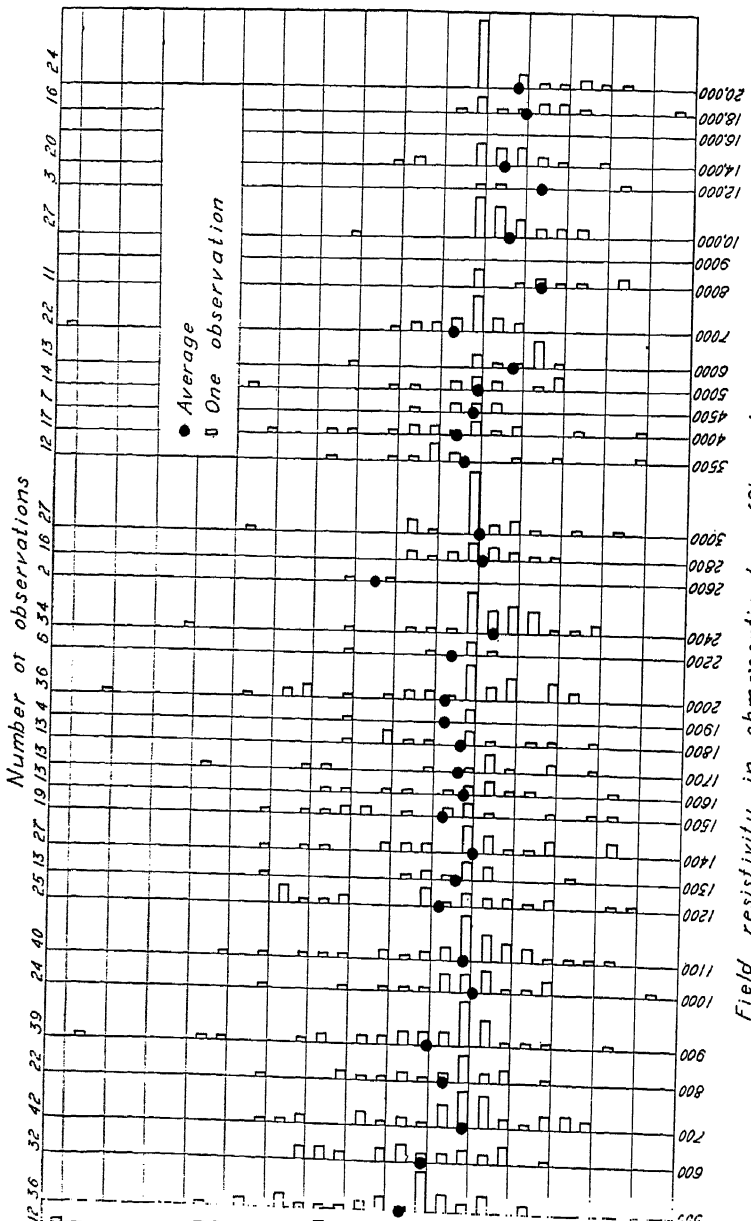

Figure 62.—*Relation of the field resistivity of the soil to the average of the conditions of the 10 sections of pipe nearest the point at which the resistivity was measured.*

The condition of the pipe was determined by visual inspection.

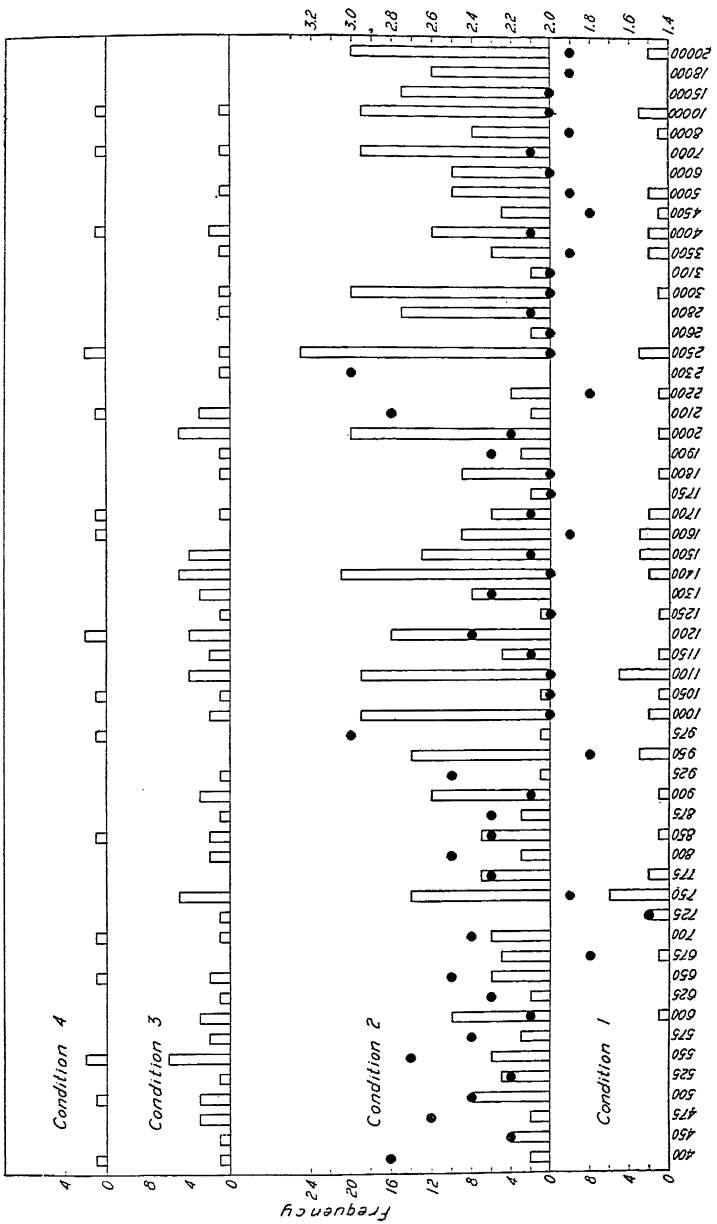

FIGURE 63.—*Relation of the resistivity of the soil to the frequency of occurrence of pipes of conditions 1 to 4 (left-hand ordinate) and to the average of the conditions of the pipes (right-hand ordinates).*

(c) CORRELATION OF PIT DEPTHS WITH SOIL RESISTIVITY AT MOISTURE EQUIVALENT

In view of possible differences in soil resistivity due to variation in moisture content, laboratory tests of the soil samples were made at moisture equivalent, which on the average represents the normal moisture content of the soil, to see whether or not this would yield a better correlation. Figure 64 shows that the correlation is, if anything, somewhat poorer, but this may be due to the smaller size and number of samples.

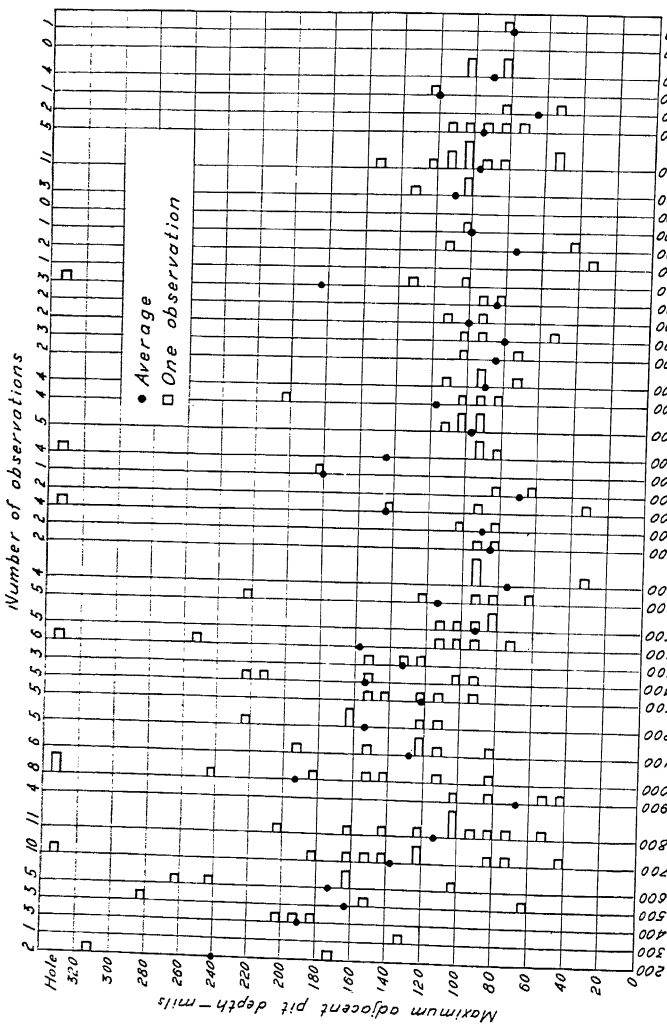

FIGURE 64.—*Relation of soil resistivity at moisture equivalent to the maximum pit depths on the sections of pipe adjacent to the places at which soil samples were taken.*

(d) CORRELATION OF OTHER SOIL TEST DATA WITH PIT DEPTHS

Correlation curves were plotted, using other criteria for corrosiveness, with similar results. Figures 65 and 66 show that the average results for all methods are similar and indicate no close correlation between any of the criteria for soil corrosiveness and pit depths. These graphs indicate

that the results of individual tests are not reliable criteria of soil corrosiveness. The explanation may be that several factors influence the corrosivity of soils and their relative importance differs for different soil conditions.

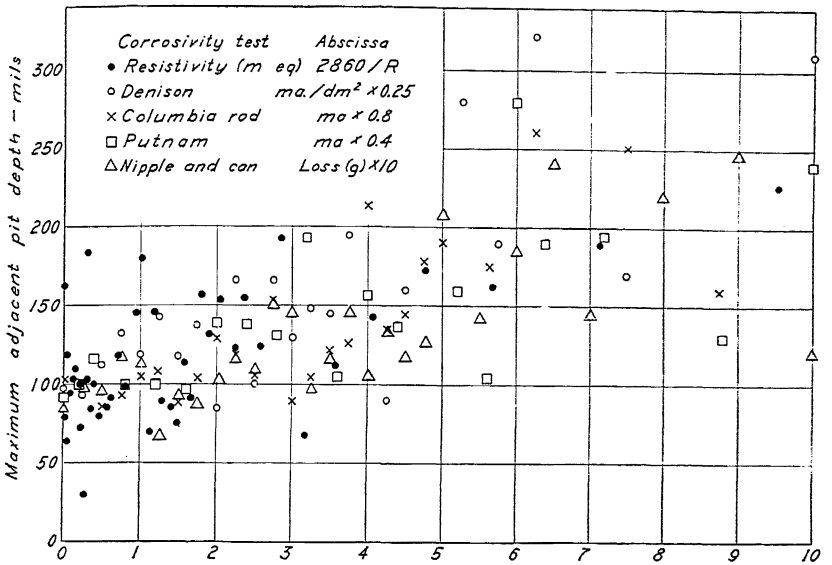

FIGURE 65.—*Comparison of corrosivity of soil as indicated by the maximum pit depths on sections of pipe adjacent to places where soil samples were taken with results of various soil tests.*

See key at top of illustration for units for the abscissa.

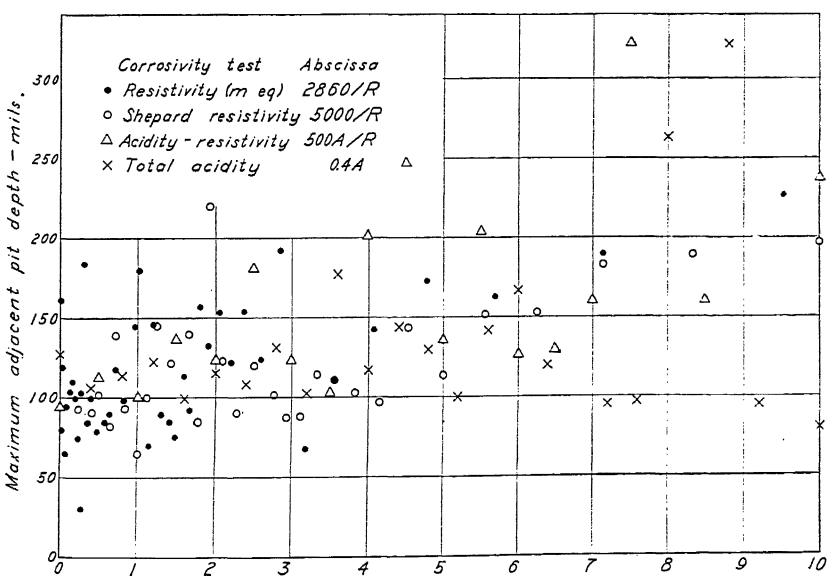

FIGURE 66.—*Comparison of corrosivity of soil as indicated by the maximum pit depths on sections of pipe adjacent to places at which soil samples were taken with results of various soil tests.*

See key at top of illustration for units for the abscissa.

For most purposes, it is unnecessary to estimate just how deep the maximum pit at some spot will be at a given time. What is more generally needed is a rough estimate of the average relative corrosiveness of the soils. All that is attempted by many corrosion engineers is to separate the soils or areas traversed by their lines into four or five classes with respect to corrosiveness because it is impractical to provide more than that number of degrees or kinds of protection for their lines. It can be shown that many of the tests under discussion are fairly satisfactory for this purpose.

(e) RELATIVE MERITS OF TESTS FOR SOIL CORROSIVITY

To determine the relative effectiveness of the tests in correctly grouping soils as to their corrosiveness, the range of pit depths was divided into five groups. The soil series were divided into five groups on two bases: (1) on the basis of the average of the pit depths on the pipe line within each series, and (2) on the basis of the average of the maximum pit depths on the sections of the line adjacent to the places where the soil samples were taken. The range of the results of each soil test method was also broken up into five groups. It should be pointed out here that the choice of all the group boundaries was entirely arbitrary and that it is possible that the relative merits of the tests would appear different if different group boundaries were used. The apparent effectiveness of one or all of the tests might also be improved by a better choice of group boundaries. Nevertheless, the groupings used will give a rough idea of the usefulness of the tests. After the group boundaries were fixed, the soil series were placed in the proper groups as indicated by the pit-depth measurements and by the results of each test and secondary tables were made to show how nearly each soil was placed in each test in its proper place as indicated by pit depths. Table 97 shows four comparisons of the test methods on the basis of the average of the maximum pit depth on the joint of pipe adjacent to the soil sample. Probably because the accuracy of the test results improves with the number of samples tested, the table shows that the percentage of the pipe line correctly assigned as to corrosion is, for most tests, somewhat greater than the percentage of the soil correctly assigned.

Many pipe line operators would be satisfied if the test came within one group of correctly classifying the soils as to corrosiveness. Table 97 shows that all but one of the tests so assigned the soil along at least 86 percent of the pipe line. The test which was least satisfactory on this basis was unsatisfactory with respect to the soil series, which was occupied by 34 percent of the pipe line. None of the tests appears most satisfactory for determining the corrosivity of all soil series.

Another similar set of comparisons based on the averages of the maximum pit depth on each joint of pipe in a soil series yields somewhat higher percentages of correct assignments for most of the tests. Table 98 shows comparisons of the test methods on two bases for each soil series and the relative values of the tests for all the series without regard to the extent of series or the number of samples tested. It is interesting to note that no one test ranked all the soils correctly or yielded the most accurate ranking for all soils. It is also of interest to note that one soil, Myatt, was apparently not correctly ranked by any of the tests and most of the tests missed the correct ranking very badly. It seems probable that the pitting in this soil was affected by some factor other than soil corrosivity, since all the tests underestimated its corrosivity. It is

TABLE 97.—*Comparison of test methods on the basis of averages of the maximum pit depths on the joint of the specimen adjacent to the soil sample.*

Soil series	Percentage of line	Shepard resistivity meter	Resistivity at moisture equivalent	Total acidity	$\frac{1000 \times \text{acidity}}{\text{Resistivity}}$	Modified Columbia rod test	Putnam test	Nipple-and-can test	Denison electrolytic cell
DEPARTURE FROM CORRECT ASSIGNMENT									
Acadia	12.96	−1	−1	0	0	0	−1	0	−1
Brown	0.38	+1	+2	−2	−1	0	+1	0	0
Caddo	24.43	0	0	+1	0	0	0	0	0
Conglomerate	2.59	−1	+1	−2	−2	−2	0	+1	+1
Crowley	2.20	−1	+1	0	0	−1	−1	−2	0
Dark brown	0.98	0	+2	0	0	0	0	0	0
Lake Charles	34.32	−1	+1	−1	+1	0	0	−2	0
Leaf	8.73	0	+1	+3	+2	0	0	0	0
Light gray	1.16	0	0	−4	−1	0	0	0	0
Myatt	4.51	+2	+4	0	+1	+1	+2	0	+2
Ochlockonee	0.88	0	+1	+3	+1	0	0	0	0
Segno	6.85	+1	+2	+1	0	0	+1	+1	+1
PERCENTAGES OF CORRECT ASSIGNMENT									
Percentage of soils	.....	42	17	33	42	75	58	67	67
Percentage of line	.....	36	26	21	47	91	73	54	73
PERCENTAGES WITH AN ERROR OF NOT MORE THAN ONE CORROSION GROUP									
Percentage of soils	.....	92	67	58	83	92	92	83	92
Percentage of line	.....	95	87	86	89	97	95	63	95

TABLE 98. *Comparison of methods of testing soils on basis of correct arrangement of soils in the rank, or order, of corrosiveness.*

Soil series	Soil rank, or order, of corrosiveness		Shepard resistivity meter			Resistivity at moisture equivalent			Total acidity			1000 × acidity / Resistivity			Modified Columbia rod test			Putnam test			Nipple-and-can test			Denison electrolytic cell		
				Deviation			Deviation			Deviation			Deviation			Deviation			Deviation			Deviation			Deviation	
	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth	Assigned rank	By adjacent maximum pit depth	By average maximum pit depth
Acadia	11	9	9	−2	0	5	−6	−4	10	−1	+1	11	0	+2	10	−1	+1	8	−3	−1	10	−1	+1	9	−2	0
Brown	8	7	11	+3	+4	11	+3	+4	4	−4	−3	5	−3	−2	9	+1	+2	11	+3	+4	9	+1	+2	6	−2	−1
Caddo	4	3 and 4	1	−3	−2	1	−3	−2	6	+2	+2	1	−3	−2	1	−3	−2	1	−3	−2	1	−3	−2	3	−1	0
Conglomerate	9	11	7	−2	−4	8	−1	−3	1 and 2	−7	−9	3	−7	−8	3	−6	−8	7	−2	−4	11	+2	0	11	+2	0
Crowley	7	8	4	−3	−4	7	0	−1	9	+2	+1	8	+1	0	8	+1	0	4	−3	−4	2	−5	−6	8	+1	0
Dark brown	1	3 and 4	2	−1	−1	4	+3	0	1 and 2	0	−1	2	+1	−1	5	+4	+1	3	+2	0	5	+4	+1	1	0	−2
Lake Charles	10	10	8	−2	−2	9	−1	−1	8	−2	−2	12	+2	+2	11	+1	+1	10	0	0	7	−3	−3	10	0	0
Leaf	6	6	6	0	0	6	0	0	12	+4	+4	9	+3	+3	6	0	0	6	0	0	6	0	0	4	−2	−2
Light gray	12	12	12	0	0	12	0	0	3	−9	−9	10	−2	−2	12	0	0	12	0	0	12	0	0	12	0	0
Myatt	2	2	10	+8	+8	10	+8	+8	5	+3	+3	6	+4	+4	7	+5	+5	9	+7	+7	3	+1	+1	7	+5	+5
Ochlockonee	3	1	3	0	+2	2	−1	+1	11	+8	+10	7	+4	+6	2	−1	+1	2	−1	+1	4	+1	+3	2	−1	+1
Segno	5	5	5	0	0	3	−2	−2	7	+2	+2	4	−1	−1	4	−1	−1	5	0	0	8	+3	+3	5	0	0
Σ	.....	.....	.....	24	27	.....	28	26	.....	44	47	.....	31	33	.....	24	22	.....	24	23	.....	24	22	.....	16	11
Rank, or order, of effectiveness of test method	.....	.....	.....	2	6	.....	6	5	.....	8	8	.....	7	7	.....	2	2	.....	2	4	.....	2	2	.....	1	1

difficult to see, however, what outside factor would greatly affect the average condition of the pipes at 10 locations or the average corrosivity of 10 soil samples. Inspection of the last two lines of table 98 will bring out the fact that several of the tests are of nearly equal reliability, but it seems probable that the relative values of these tests might be different if soils from some other part of the country had been tested.

Although the above comparisons of test data with corrosion are based on what are probably the most detailed and specific data available, they are not entirely satisfactory because of the lack of precision of all the classes of data involved. Other comparisons of soil resistivity with pit depths on pipe lines have been published by Weidner and Davis [112], Fitzgerald [113], Gill and Rogers [114], and Ewing [115]. Putnam [52] has shown the correlation between the results of his soil testing method and the loss of weight and pit depths of the National Bureau of Standards specimens, and Denison [95] has made a similar report on his method.

XI. DETERMINATION OF THE CONDITION OF A PIPE LINE

1. LOCATION OF CORRODING AREAS ON PIPE LINES

Soil tests such as those described in the preceding sections are used to locate places along a right-of-way where corrosion may be expected because of local soil characteristics.

It has been pointed out that the effects of the soil are modified by the way in which a trench is backfilled, by the interaction of adjacent soils, by currents picked up by the pipe line, and possibly by other factors. After a pipe line has been laid, it is advisable to determine not only if it lies in potentially corrosive soil, but also the points where the line is actually corroding. Several methods have been devised for doing this, based on the fact that corrosion is associated with differences of potential and a flow of current.

(a) MEASUREMENTS OF POTENTIALS AND CURRENT

If the resistivity of a pipe is known, the current in the pipe can be calculated from the difference of potential between two points on the pipe a known distance apart. The measurement of the current in the line from point to point provides data that indicate whether the line is collecting or discharging current. The discharging areas are those at which corrosion is occurring. Contact is usually made by driving steel rods into the earth over the pipe. Care must be taken to avoid or correct for contact resistance. Measurements of pipe-line currents have been described by several authors [97, 116, 117, 118, 119].

Usually the potential values are not reduced to currents. If the measurements are made between equidistant points, the change in value will indicate whether or not the pipe is collecting current. The point of maximum corrosion is usually that toward which current flows from both directions. The currents are seldom more than a few amperes and more often only a fraction of an ampere. Sensitive instruments are, therefore, required to measure the drop of potential along a pipe, especially if the pipe is large, and care must be taken to avoid spurious potentials caused by thermal and other effects. These difficulties can be avoided, at the risk of incurring others, by measuring potential gradients in the earth either over the pipe or in a direction at right angles to it. In such measurements the potentials of the contact electrodes must be con-

sidered as well as the contact resistance. If, as is usually the case, the resistivity of the soil varies from point to point, the effects of this variation must be considered also.

Mudd [120, 121] has reported success with a combination of current and potential measurements. Schlumberger and Leonardon [122] have described a method of locating corrosion by observations at the surface of the earth and have developed and patented apparatus for this purpose. Current flowing to or from pipes can be measured directly by apparatus devised by Pearson [123], Haber [124], and McCollum [125]. These devices are of value chiefly in measuring directly fairly large currents in the earth. All the methods and apparatus, except the last two, measure the current discharged from a considerable area of pipe and disclose only the average current density of the discharge. They, therefore, give data for computing the average rate of loss of weight or the average rate of penetration but do not show directly what the maximum rates are, and it is the maximum rate which determines the time required for the development of a leak.

For small areas exposed to approximately uniform conditions, the ratio of the maximum to the average penetration is in the order of 10 to 1, but for larger areas, such as that of a 20-foot length of 8-inch pipe, the ratio may be much larger. In a line with a good protective coating, all the current may be discharged from a very small area where the coating has been injured. If the anodic and cathodic areas are separated by distances much greater than the distance across which the potential difference is observed, much of the corrosion current will affect the observation. If the anodes and cathodes are close to each other, as on the bottom and sides of the pipe, the total current will not be observed.

In general, the computed value of current will be much less than the total current and, therefore, it will be insufficient to account for the observed corrosion. In addition, the so-called long-line currents have been found to change from time to time, probably because of changes in soil moisture or aeration. Obviously, therefore, no close correlation between corrosion and long-line currents can be observed, and if most of the corrosion results from very local circuits, there will be none at all, as claimed by Gill and Rogers [114], who also concluded that soil resistivity was of no practical value in determining corrosion. These conclusions are not in agreement with those of other equally experienced corrosion engineers [112, 115]. The disagreement may be accounted for partly by the differences in the soils involved, partly by differences in methods and apparatus and partly by the standards by which the data are judged, and by what the engineers may have in mind as alternatives for accomplishing the same purpose.

(b) COUPONS

Coupons are small iron or steel plates buried near a pipe line to determine the corrosivity of the soil or, if the coupons are connected to the pipe, the rate of corrosion of the pipe. They are used in a number of ways by different corrosion engineers, and there is a considerable difference of opinion as to their usefulness. Schneider [126] cites a number of cases of close agreement between pipe life and predictions based on the use of coupons.

A number of theoretical objections to the use of coupons have been raised. There may be a difference of potential between the coupon and the pipe because of a gradient in the earth or because of rust or mill scale

on the pipe surface. The soil surrounding the coupon may not be representative of that around the pipe. If current flows to or from the pipe or coupon, the current density will not be the same on the two because there will be a tendency for current to collect on or discharge from the edges and corners of the coupons. If these factors are negligible, attached coupons serve a useful purpose as indicators of the rate of corrosion of a bare or imperfectly protected line. They can also be used to determine whether a line to which they are attached discharges or collects current. However, the pipe as a whole might be cathodic and still have anodic spots, such as the bottoms of pits.

2. INSPECTION AS A MEANS OF DETERMINING THE CONDITION OF A PIPE LINE

As it is usually impracticable to examine an entire pipe line periodically, the problem of the number and extent of the examinations necessary to furnish representative data arises. This question was investigated jointly by the American Petroleum Institute and the Interstate Commerce Commission. The Commission concluded that for the purpose of determining the condition of the line for rate-making, inspections of the line at selected places and intervals were unnecessary. The decision was reached partly because the cost of an adequate number of inspections would be excessive and partly because for rate-making purposes obsolescence was considered to be the controlling factor. In the case of one pipe line [127], an agreement was reached that the life of new wrought iron and steel pipe would be considered to be 33⅓ years and that the life would be increased 3 to 7 years by bituminous protective coatings, depending on the number of reinforcing layers. The data upon which the agreement was reached were not published. Obviously, such a basis would not be satisfactory for determining the physical condition of a section of a line in order to decide whether or not it requires reconditioning, protection, or repairs.

Gill [128] concluded, from statistical considerations, that a line should be inspected at equally spaced points, and that 2,000 feet was the greatest permissible distance between inspection points. Such inspections convey an idea of the average condition of the line, but only detailed inspection of the data will reveal where corrosion is in progress.

Logan and Koenig [129] made statistical studies of pit depths on pipe lines, including one 200-mile length on which the deepest pit on each joint of pipe was measured. They attempted to show the different factors affecting the results of inspections, including the space interval between the sections inspected, the number of inspections, the location of the starting point from which equally spaced inspections were made, and the effect of the size of the area inspected on the observed average maximum pit depth.

Each of the first eight columns in figure 67 represents the average depth of the deepest pit on each 25 joints (20 feet long) of 8-inch pipe. The inspections were made at 1-mile intervals. The different columns represent the data for eight different starting points separated by ⅛-mile intervals. In two cases the computed average differs from the true average by about twice the standard error, whereas, for normal data, the probability of such an occurrence is but 1 in 20. It is evident that for a comparatively few inspections the starting point may affect the data. The next four columns in figure 67 show the results of 4 sets of 50 inspections of the same line. None of the computed averages differ

from the true average by more than the standard error which, of course, is smaller than that for 25 observations. The last two columns in the figure indicate that the reliability of the average is only slightly increased by increasing the number of inspections to 110, i.e., making the inspections at ¼-mile intervals. This conclusion applies strictly, of course, only to the section of the line under consideration.

Figure 68 shows the effect of the area inspected and of the starting point for 30 inspections of a line at 1-mile intervals. As the area inspected is increased, the effect of the starting point is decreased, as is also the standard error of the average, even though the number of inspections is constant.

The relation between the inspection interval, starting point, and number of inspections when the corrosion criterion is the condition of the pipe is illustrated in figure 69, supplied by the Stanolind Pipe Line Co. The figure indicates, as did figure 67, that if the number of inspections is small, the average is affected by the starting point of the inspections.

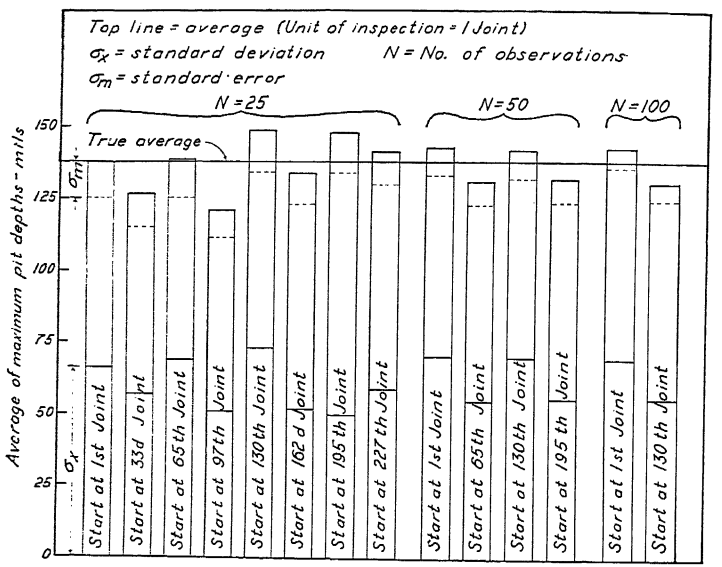

FIGURE 67.—*Effect of the starting point and the number of inspections on the observed average of maximum pit depths on sections of a pipe line.*

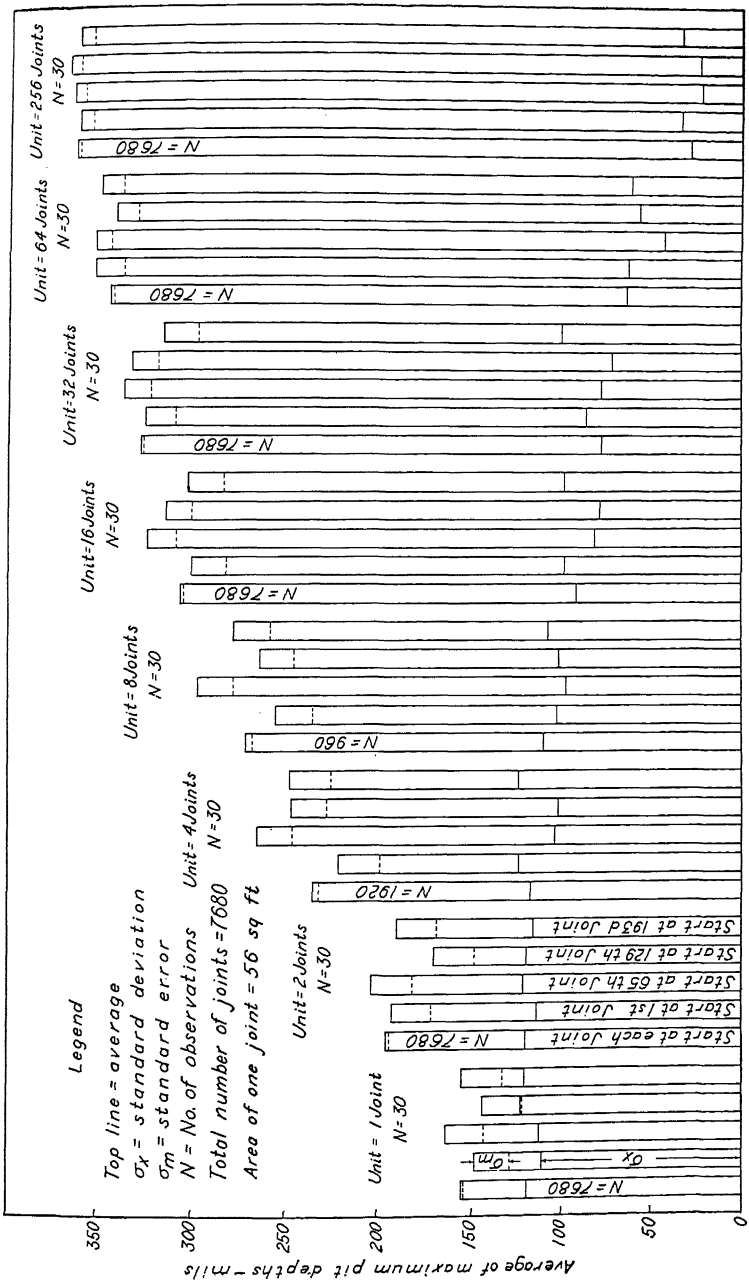

FIGURE 68.—*Effect of the point at which inspections were started and the area inspected on the computed average of the maximum pit depths.*

Note that the value of the pit depths increases as the area inspected increases.

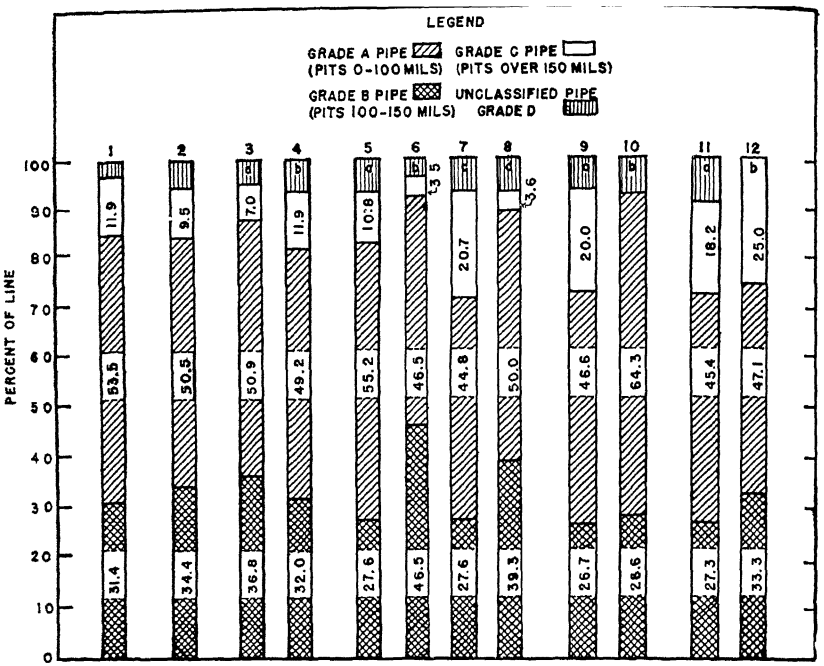

FIGURE 69.—*Effect of method of inspection on apparent condition of a pipe line.*

Inspection intervals:
(1) .....Complete inspection
(2) ..... 500 feet
(3 and 4).....1,000 feet
(5 to 8).....2,000 feet
(9 and 10).....4,000 feet
(11 and 12).....5,000 feet

Inspection data:
11.4 miles of pipe line.
Laid in 1914, taken up in 1934.
One 20-foot joint of pipe is inspected at each inspection point.

The relation between the size of the area inspected and the depth of the deepest pit and the effect of the area on the reproducibility of the data are important considerations in determining how much pipe should be exposed at each inspection point and the frequency of inspection (fig. 70).

The lower curve is based on data from a 9-year-old 12-inch steel line exposed to a heavy clay soil, assuming that an inspector started at 48 different points on the line and first uncovered 1 foot of pipe and measured the depth of the deepest pit. The trench was then extended 1 foot and the depth of the deepest pit on the 2-foot section was measured. Similarly, the depth of the deepest pits on greater lengths up to 20 feet were measured. The curve indicates that the average depths of the deepest pits increase as the area inspected is increased, but that when a large number of observations (48) is made, the standard error of the average (one-fourth of the length of the vertical lines) does not decrease very much. The average of the values obtained by a large number of inspections of 1-foot lengths is almost as representative as the averages of the values obtained on entire joints of pipe. This conclusion would not hold if only a few inspections of 1-foot lengths of pipe were made, as the pit depth on a length of pipe varies greatly from foot to foot. The upper curve indicates that each inspection point would have to include a large number of lengths of pipe before the value of the average maximum pit depth would become substantially constant. The curve also indicates

that when this area is reached, the number of observations require for a specified degree of reproductibility decreases as the area examine is increased.

Logan and Koenig suggested that, since corrosion appears to b characteristic of the type of soil to which the pipe is exposed, and sinc the same type may occur in several places along a long right-of-way the number of inspections necessary for determining the condition c the line might be reduced by first identifying the soils traversed by th line and then making in each soil only a sufficient number of inspection to establish its corrosiveness. In addition to reducing the number o inspections, this procedure would furnish data as to the location of th sections which need reconditioning or protection. The relation of soi types to corrosion has already been discussed and is illustrated in figure 50 and 51.

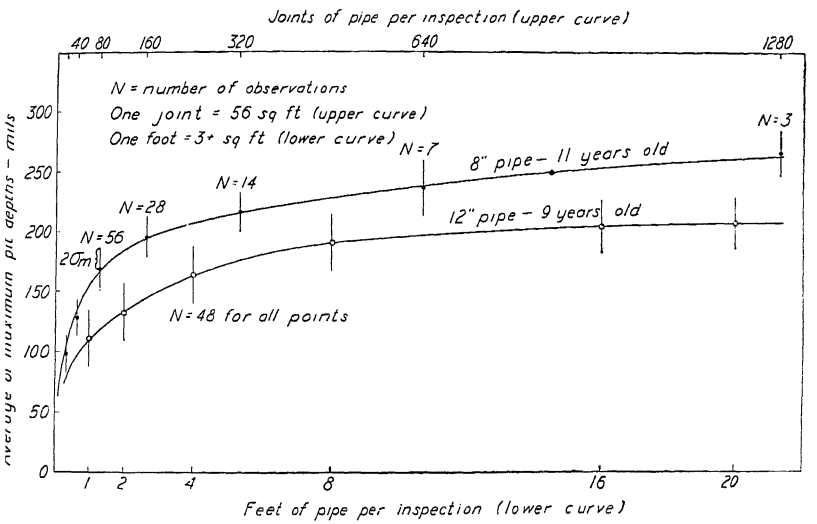

FIGURE 70.—*Relation of area of pipe inspected to the maximum pit depths on each area.*

All investigators seem to agree that a large number of inspections is esssential to an accurate determination of the condition of the pipe. If the number is adequate, the size of the area is unimportant, but the number of inspections required for a certain precision of the results will increase as the area inspected is decreased.

The conclusion that pipe should be inspected at equally spaced distances or with regard to soil types is based on the assumption that the condition of the entire line is desired, as for valuation purposes. If the operator of the line has had considerable experience with corrosion and is interested only in anticipating leaks, he may follow the practice of the Susquehanna Pipe Line Co. described by Van deWater [130]. This organization inspects its pipe at places where abnormal corrosion is likely, such as at low spots, bogs, swamps, and highway and railroad crossings. Locations where a leak would be particularly dangerous are also examined. Thousands of places on a line extending through Pennsylvania and Ohio have been thus inspected. From 7 to 10 feet of the pipe are exposed at each inspection point, and

from 10 to 15 pit depths are measured. Examinations cost about $10.00 each and average about $65.00 per mile of line. About 10 percent of the line has been protected. This is accomplished by boxing the pipe and filling the box with asphalt. The protected sections range from 20 to several hundred feet in length.

XII. TESTS OF COATINGS

Various tests have been devised for determining the suitability of a coating for a given kind of service or its condition either before or after exposure to corrosive soils. In general, they are used to determine thickness, continuity, electric resistance, or mechanical strength.

1. METALLIC COATINGS

The use of metallic coatings underground is not general enough to warrant an extended discussion of methods of test of such coatings. The effectiveness of a metallic coating depends in part on its thickness, and this factor should be taken into consideration in comparing or specifying metallic coatings for pipes or tanks. The potential of the coating with respect to the underlying metal is also important because galvanic corrosion may occur if both metals are exposed to the soil.

Burns and Schuh [30] have described a number of tests that may be classified as (1) stripping tests, in which the loss of weight of the coated metal is determined after removing the coating, (2) solution tests, in which the time required for rust to appear is determined when the coating is subjected to the action of certain corrosive solutions or sprays, (3) electrolytic tests, in which current is passed from the coated metal to a paper in which the anion from the underlying metal is precipitated, (4) the chord test, in which the coating is cut at a definite angle and its thickness measured with a microscope. These tests, with the exception of the electrolytic test, are destructive, and their usefulness therefore is limited mainly to investigational work.

2. INSULATING COATINGS

The principal causes of failures in insulating coatings are faulty application, injuries, pinholes, decay, and distortion resulting from what Scott [131] calls soil stress.

Tests for continuity and resistance have been developed by Ewing and Scott [132]. The section to be tested is first washed and then painted with a slurry of kaolin or iron-free clay and water to fill holes, cracks, and depressions. A sheet of absorbent paper known to plate printers as wiping paper and sometimes sold as pinhole paper is placed over the clay and is wrapped with several layers of water-soaked cotton flannel 1 foot wide. The pad is held in place by a saddle consisting of a framework of copper strips, as shown in figure 71. A 22-volt battery is connected between the saddle and the pipe, the pipe being made the anode. The circuit is closed until the product of the applied voltage and the time in minutes is approximately 100. The paper is then removed and washed in a 1-percent solution of potassium ferricyanide. If current flows from the pipe through openings in the coating, ferrous oxide will be deposited in the paper, which will cause blue spots to appear corresponding to the holes in the coating upon treatment with potassium ferricyanide. As the number and size of the spots are indications of the condition of the coating, this test is known as the pattern test for coating

continuity. The pattern test is helpful in locating small pinholes and cracks; patterns from different coatings, however, are not comparable unless the resistivities of the waters used and the voltage-time products are the same for each coating.

If the current and voltage supplied by the battery as used in the pattern test are observed, the resistance or conductance of the coating can be calculated. The latter is usually expressed as micromhos per square foot. Although the conductance measured in this way involves the conductances of the pad, paper, and test solution, these are usually negligible if the coating is good; there is nothing to be gained by testing a coating with an obvious hole. As the range of conductance values of coatings is very large, a special instrument, such as that designed by Shepard [74] for measuring them, is desirable.

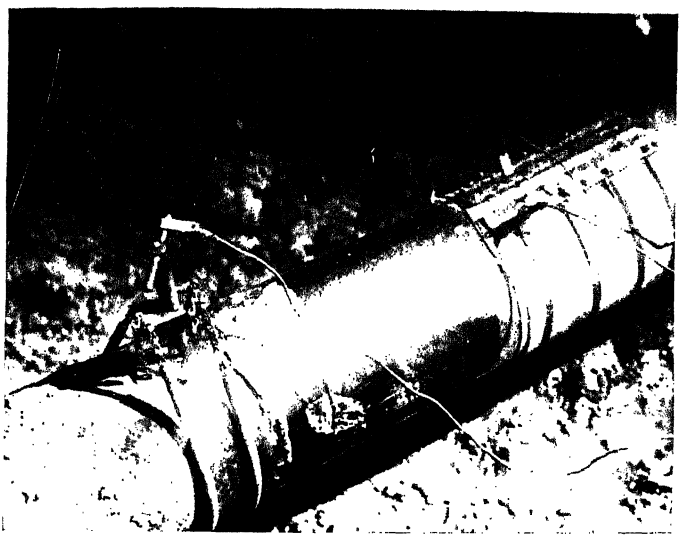

FIGURE 71.—*Setup for making pattern and resistance tests of pipe coatings.*

The pattern and conductance tests are, of course, applicable only to small areas of coatings after they have been exposed to soil or water long enough to permit the moisture to pass through any holes in the coating. There are two other types of continuity tests that are applicable to coated lines and which can be used to determine the condition of large areas of coatings. One of these is a high-voltage or spark test intended primarily for the detection of pinholes.

The apparatus, figure 72, consists of a high-voltage transformer, or induction coil such as a Ford spark coil, a battery, a current interrupter, and an insulated metal brush. One side of the secondary of the coil is attached to the pipe and the other side to the brush. The battery and interrupter are connected across the primary of the coil. As the brush is passed over the surface of the coating a spark will jump to the pipe when the brush is over a pinhole or holiday; the sound and flash of the sparks thus locating the flaws in the coating. Clarvoe [133] and Harrell [134] have described such apparatus and its use. These detectors have several faults. The operator may skip some of the coating area. The high voltage may break down the coating if it

is applied too long at one spot. The voltage may be too low if the coating is very thick. Most forms of the apparatus do not locate thin spots in the coating. If the output of the transformer is high, accidental contact with the secondary circuit may cause a serious accident. Such holiday detectors have been used extensively and have been instrumental in the production of better coatings. Their use is specified in many contracts for coatings. Recently, Stearns [135, 136] patented an improved form of detector that travels over the pipe in such a way that the missing of a pinhole is unlikely. The apparatus operates a counter, lights a colored light, and rings a bell whenever a spark jumps to the pipe. The voltage of the apparatus can be controlled. After a spark has passed, the high voltage is cut off for 1 second.

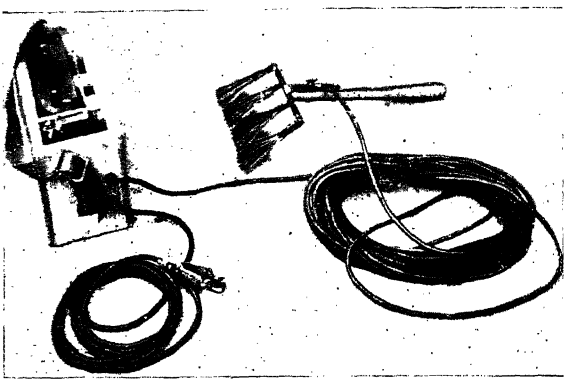

FIGURE 72.—*Apparatus for locating pinholes in bituminous coatings.*
It consists of a Ford spark coil, dry batteries, and a metal brush with an insulated handle.

Although the use of a holiday detector may insure the application of a continuous coating, it does not insure a continuously coated pipe, because the coating may be injured after the test especially in the course of laying the coated pipe. In addition, the coating may be punctured by roots, as illustrated in figure 73, or it may crack after it is in the ground. The apparatus described by Pearson [137] is therefore of interest. A 1,000-cycle battery-driven hummer is connected between the coated pipe and a rod driven into the ground a 100 feet away. Most of the current that passes from the pipe to the ground rod must flow through holes in the coating. This results in an increased IR drop of potential in the soil opposite the holes. The disturbed earth potential is located by two men 20 feet apart, one of whom carries an amplifier and indicating meter, the other man providing the ground connection. Each man has steel cleats on his shoes, connected in the first case to the amplifier shielding and in the second case to the amplifier input by means of a shielded cable. They walk along the pipe line as nearly over its center as possible. When either man passes over a hole or poorly insulating spot in the coating there is an increase in the deflection of the indicating meter and in the sound in the earphones in parallel with the meter. Although the use of the apparatus requires some experience, its effectiveness has been demonstrated by several users. Pearson [137] has published details concerning the design and use of the apparatus. It will locate individual pinholes and other openings in an otherwise good coating or areas of poor coatings if pinholes or carbonized particles are

too numerous to make a single defect outstanding. In this article Pearson also describes a method for measuring the resistance of a coating on a pipe line without uncovering the line.

In order to compare the ability of different coatings to withstand soil stress, Ewing [109] constructed an outdoor soil box in which the conditions producing the stress could be simulated. The box, about 1

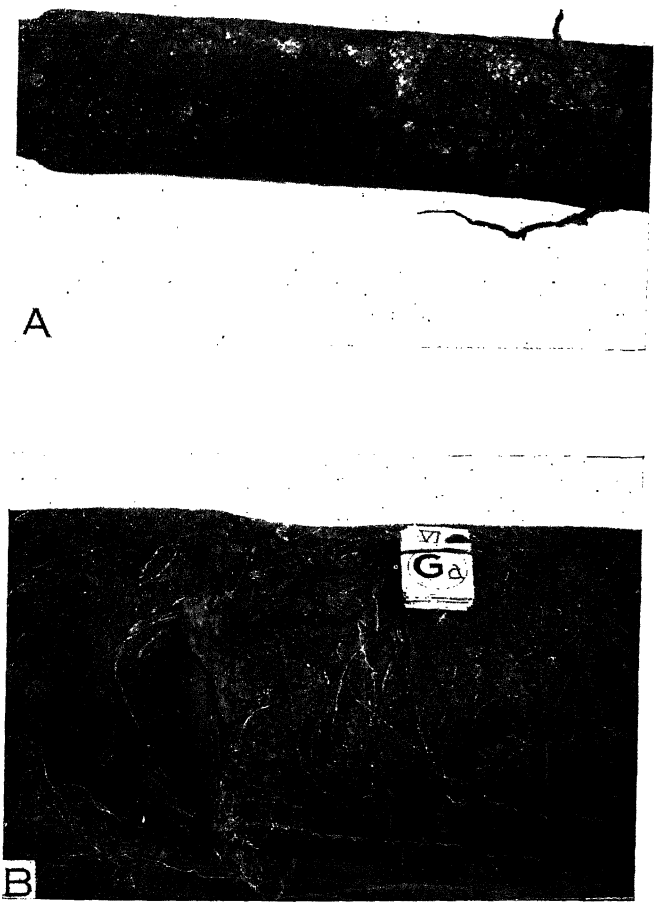

FIGURE 73.—*Coatings injured by roots.*

A, Root beneath a rag-felt-reinforced asphalt coating; *B*, grass roots in and beneath a 10-year-old asbestos-felt shielded coal-tar enamel coating on a pipe line in Oklahoma.

foot in depth was constructed of porous brick supported above the ground to provide the greatest possible surface for evaporation. The specimens under investigation were first subjected to the pattern test and then buried in the box so that there was about 6 inches of dry soil above the specimens. Since the available soil did not have a sufficient

volume shrinkage between saturation and complete dryness, it was modified by the addition of about 1 percent by weight of sodium carbonate (washing soda) which increased the shrinkage from 28 percent to about 53 percent. By alternately wetting the soil and letting it dry, the samples were subjected to a number of cycles of stress and then examined. Soft coatings were found to be distorted, but not so much as some specimens observed in field tests, probably because the soil in shrinking tended to pull away from the sides of the box instead of from the coating. There is a difference of opinion as to whether the distortion results from a pull when the soil shrinks or from pressure when the soil swells as it absorbs moisture.

Ewing also tried impact tests by dropping a steel ball weighing 1.65 pounds from various heights and noting the minimum height at which a failure was produced as indicated by an electrical test. He found that the test, as he applied it, involved several variable factors difficut to control.

3. TESTS OF COATING REINFORCEMENTS AND SHIELDS

To reduce distortion of bituminous coatings by clod pressure, pipe movement, and soil stress, the bitumen is frequently reinforced by a spiral wrapping of fabric, which may be an open-mesh woven cotton

TABLE 99.—*Character of pipe-line fabric materials and results of breaking tests.*

No.	Description of material	Weight	Thickness	Ratio of strength of bottom half of specimens after exposure of 301 days to original strength[1]
		lb/100 ft²	*Mils*	
	14-lb. asbestos felt, asphalt-saturated..	13.9	26.7	0.88
	15-lb. asbestos felt, asphalt-saturated...	17.0	28.1	.87
	15-lb. asbestos felt, tar-saturated.....	14.6	29.5	.49
	14-lb. asbestos felt, tar-saturated.....	13.7	27.4	.745
	Same as 1 with bakelite resin saturant.	12.4	25.9	.48
	15-lb. asbestos felt, tar-saturated.....	15.1	28.7	.93
	15-lb. asbestos felt, grease-saturated....	15.8	28.6	.445
	15-lb. rag felt, asphalt-saturated.....	17.3	41.6	.21
	30-lb. rag felt, asphalt-saturated.....	32.3	69.8	.22
	30-lb. coated rag felt, asphalt-saturated.	30.2	55.2	.25
	40-lb. coated rag felt, asphalt-saturated.	47.4	96.8	.26
	15-lb. rag felt, tar-saturated.....	15.5	40.4	.00
	30-lb. rag felt, tar-saturated.....	26.8	65.2	.07
	Polymerized resin shield.....	5.5	10.5	.12
	Polymerized resin shield, paper-backed.	9.3	19.7	.105
16	Cotton fabric with rot inhibitor, grease-saturated.....	8.7	21.0	.11
17	Cotton fabric without rot inhibitor, grease-saturated.....	8.0	18.5	.0
18	Woven asbestos fabric, open weave, tar-saturated.....	21.5	73.0	1.37
19	Cotton fabric, asphalt-saturated.....	8.05	32.7	0.00
20	Cotton fabric, tar-saturated.....	8.25	33.7	.00
21	Coir fiber, close weave.....	22.0	97.7	.00
22	Burlap.....	7.8	26.0	.00
23	Manila fiber.....			.00
24	Manila fiber, creosote-treated.	25.4	111.1	.16
25	Hemp.....	46.5	188.1	.00
26	Sisal.		214.7	.00

[1] Based on average strength after soaking. The measurements of February 1934 and January 1935 were used.

fabric of the Osnaburg type, burlap or bitumen-saturated rag, or asbestos felt. This wrapping may be covered with bitumen, in which case it is called a reinforcement, or it may be left exposed directly to the soil, in which case it is called a shield.

To determine the effect of soil, or rather of soil bacteria, on these materials, Scott and Ewing [138] exposed 26 varieties of these materials to a soil obtained from the flood plain of a river near Washington. Strips of the materials were buried in boxes of the soil, which was saturated at intervals of 1 month. Table 99 shows the character of the materials tested and the strength of the materials after 301 days of exposure in terms of their original strengths. It indicates that all the organic materials deteriorate when exposed to soil bacteria. The materials were exposed directly to the soil, and some were not impregnated with bitumen or treated to resist rot. In service, they might be saturated with bitumen and covered by a fairly thick layer of this material. Under these conditions, they should last much longer.

When Ewing [139] removed the first set of AGA specimens of coatings, he desaturated the fabrics and then determined their strength. He observed little or no deterioration of the fabrics saturated with coal tar after 9 months of exposure to organic soils, but the organic fabrics in asphalt coatings had deteriorated. He found also that the rotting decreased with increased thickness of the asphalt over the fabric, and that muck soils were the most destructive to the fabrics.

XIII. PREVENTION OF CORROSION

The investigations reported in Section XII were carried out to obtain data on the relative corrosiveness of various soils, the relative resistance to corrosion of various materials commonly used underground, the influence of various factors other than the inherent corrosiveness of a given soil on the rate of corrosion of a material buried in it and to develop methods preventing or minimizing losses due to corrosion. The protection to use in a given case is dictated by economic considerations and depends upon a variety of factors. If obsolescence is an important factor, the added expense involved in protecting a pipe line so that it would last a very long time might be unjustified. In any event, the increased cost of any protective measure which might be adopted, including the annual charges on the increased cost, should be balanced against the cost of replacement or repairs. Special protection may be unnecessary or unduly expensive in soils that are only mildly corrosive. On the other hand, more severe conditions may require some protective measures, such as the use of corrosion-resisting materials, special treatment of the soil, protective coatings or cathodic protection.

1. MATERIALS SUITABLE FOR USE IN MILDLY CORROSIVE SOILS

According to the data presented earlier, the different ferrous alloys commonly used in pipe corrode at approximately the same rate. In some soils wrought iron has a tendency to corrode somewhat more uniformly or to show a slightly lower average penetration than other metals. In a few alkaline soils, cast iron appears to have a somewhat higher rate of penetration, but this may be compensated for to some extent by the strength of the corrosion products. The differences, however, are not very great. From this, it would appear that, at least in mildly corrosive soils in which bare pipe would ordinarily be laid, the thickness of the pipe wall is more important than the material of which the pipe is made.

If a pipe line is to be laid in a soil that is only mildly corrosive, the length of service will depend primarily upon the wall thickness of the

pipe. In some soils (table 51) a light-weight steel pipe will render many years of service without a leak. Under such conditions, a pipe only heavy enough to withstand the internal and external pressures with a reasonable factor of safety may prove to be the most economical.

The pit-depth–time factors (table 51) indicate that a moderate increase in wall thickness of a pipe may be expected to greatly increase its useful life in many soils. Figure 16 and curves plotted from the pit-depth–time equation show the required wall thickness for a given average pipe life before puncture and indicate that in many soils it is practicable to obtain long service life by means of a moderately thick pipe wall. Such curves are based on average values and considerably thicker pipe walls should be used if entire freedom from punctures is desired. It may not be economical, however, to use a very thick pipe in order to secure a long life. Obsolescence and the annual charges on the increased cost of the longer-lived pipe may outweigh the advantage of the longer service.

2. CORROSION-RESISTANT MATERIALS

Various attempts have been made to reduce losses due to corrosion in the more corrosive soils by the use of noncorrodible or corrosion-resistant materials. Many early water pipes were made of board logs and, later, of pipes made of wood staves held in place by metal bands. If kept con-

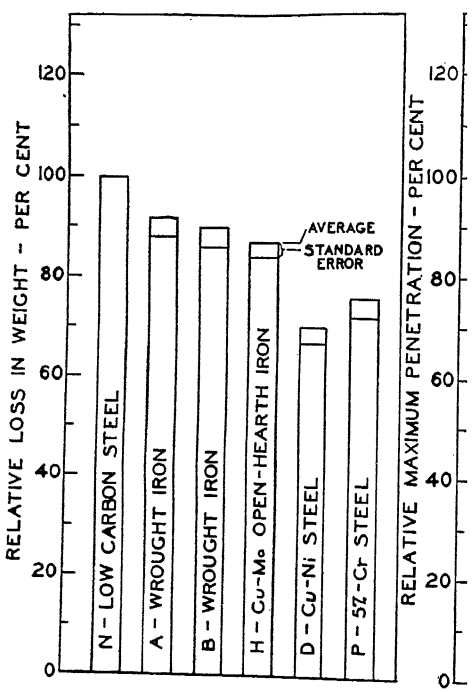

FIGURE 74.—*Relative loss of weight and penetration of wrought ferrous specimens. Low carbon steel=100 percent.*

tinuously wet, these pipes often last for many years, but under some conditions the wood-stave pipes leak badly and the metal bands corrode and break.

Cement and concrete, usually reinforced with steel, have been em-

ployed extensively for water, especially for large volumes at low pressures. For many years in Europe, and more recently in the United States, pipes made from a mixture of cement and asbestos have been used. Some data on this type of pipe were given earlier (page 128), but they do not cover a sufficient period of exposure to warrant definite conclusions, although they appear to be satisfactory from the corrosion standpoint. For sewers and drains, virtified tile is satisfactory as far as corrosion is concerned.

In most soils, copper and copper-rich alloys corrode much more slowly than iron or steel and the corrosion is more uniform. There are not enough data to indicate definitely how the rate of corrosion in copper and copper alloys varies with time, but apparently the rate of corrosion becomes nearly constant after a short time if the soil conditions do not change. If copper or copper alloys are used in conjunction with ferrous materials, they should be connected by insulating joints to prevent accelerated corrosion by galvanic action. Muntz metal (60% Cu, 40% Zn) is unsuitable for service in many soils on account of dezincification, but

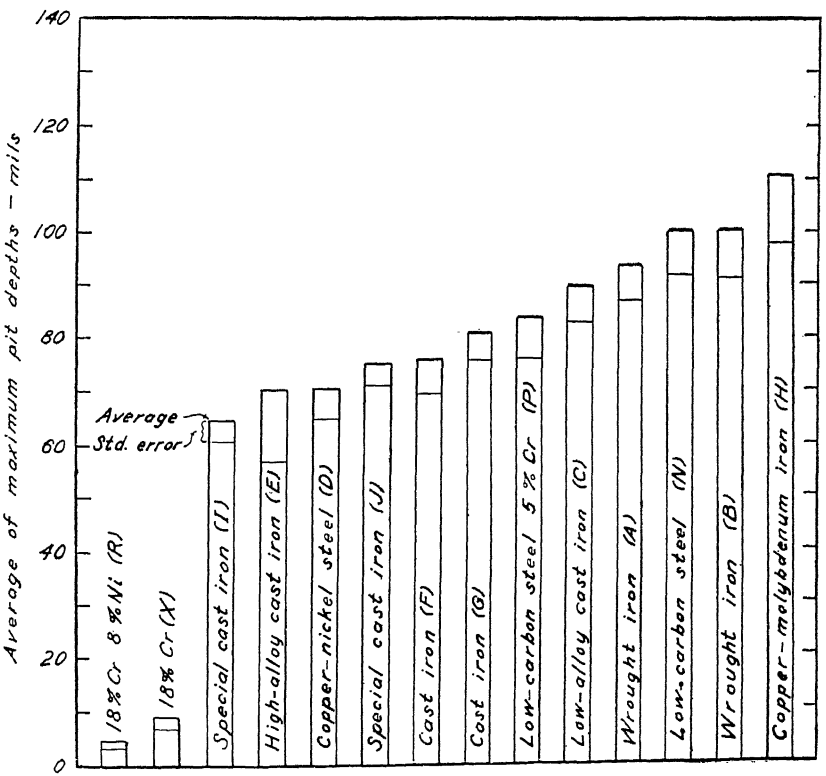

FIGURE 75.—*Average of maximum pit depths on ferrous pipes removed from Merced clay adobe after an exposure of 5 years.*

corrodes less rapidly in tidal marshes, even though it is subject to some dezincification. Lead pits badly in a few soils, but corrodes little in others, especially those containing sulfates.

Ferrous metals can be made more resistant to corrosion by the addition of certain alloying elements, such as copper, chromium, or nickel.

It has been found, however, that small additions of these elements are not effective for underground service. This is shown in figure 74. Steels containing appreciable percentages of chromium and nickel corrode very little underground (fig. 75). Except in a relatively few soils, cast iron containing 15 percent of silicon does not corrode appreciably but unfortunately this alloy cannot be easily machined or welded. The use of ply metal, that is, corrodible metal surrounded by a thin layer of corrosion-resistant material, such as copper or stainless steel, has been suggested. One such material was included in the National Bureau of Standards tests, but little or none of this material is in service underground. Copper-clad steel is quite generally used for ground rods and similar purposes. As suitable corrosion-resistant materials are expensive, it is usually more economical to employ other means for reducing losses due to corrosion, with the exception perhaps in the case of small-diameter pipe or when corrosion might result either directly or indirectly in serious losses.

3. SOIL TREATMENT

Soil treatment may consist in (1) the addition of chemicals to neutralize the corrosive properties of the soil or to accelerate the formation of protective films, (2) the replacement of corrosive soil next to the pipe by less corrosive soil, or (3) drainage.

Attempts to prevent corrosion by the neutralization of the corrosive properties of the soil are based largely on a misunderstanding of the chief cause of underground corrosion. Only a very few soils are chemically corrosive. To be effective, an added chemical must be in solution and in this condition it will be rapidly removed from the neighborhood of the pipe by diffusion and the movement of water in the soil. Hydrated lime and ground limestone are the chemicals most commonly used, because they are moderate in price and only slightly soluble. To minimize losses by diffusion, Grodsky [140] proposed to surround the pipe with a waterproof membrane and place soil mixed with sufficient lime or other agent to neutralize its acidity between the membrane and the pipe.

The use of lime has been stimulated by the observation that, frequently, pipes in soils containing lime are coated with a thin scale of calcium carbonate and that the pipe beneath this scale is not seriously corroded. There appears to be little available information as to the extent of the use of lime to neutralize soil in trenches or of the success of such use. The Dutch Central Corrosion Committee [6] reports the examination of a 9-year-old pipe laid in a bog. The pipe was surrounded by a layer of sand to which lime had been added. Analysis of the sand showed that it contained 5.1 percent of $CaCO_3$ and had a pH of 7.9. The pipe was not corroded, except at a point where the sand was no longer in contact with the trench.

Wichers [141] made extensive studies of underground corrosion in Groningen, Holland, and suggested three methods of improving soil conditions: (1) using impermeable earth for the upper layers of the trench and drainage where necessary, (2) kneading plastic clay or loam around the pipe, and (3) surrounding the pipe with sand or earth neutralized with lime. Clay and sand have been used to surround short stretches of pipes in the United States, especially when the pipe passed through made ground containing cinders. The practice is not general and no definite results have been reported but no doubt these materials are less corrosive than cinders and rubbish. More often a heavy bituminous coating or one of concrete is used for such conditions.

4. PROTECTIVE COATINGS

The most common method of reducing losses due to corrosion underground is by the application of some form of protective coating. The coatings ordinarily used on the larger pipes are nonmetallic, but zinc-coated (galvanized) pipe is extensively used in the smaller sizes, especially for water services.

Kelly [142] states that approximately half of the steel pipe currently in service is protected by some form of coating, and that 80 percent of such pipe is covered with a tar-base coating. Excepting the dip coating applied to nearly all cast-iron water mains, the most commonly used coal-tar coating is an enamel made by adding finely divided inert material to coal-tar pitch. Coatings of concrete or grease are also used to a certain extent.

(a) CONCRETE

Concrete and cement-motar coatings have been used extensively by certain pipe line companies when corrosion is very severe. The earlier cement coatings were applied after the pipes were in the trenches by placing boards 1 to 2 inches from the pipe and filling with mortar. Sometimes no board was placed beneath the pipe, and occasionally mud was forced ahead of the mortar and into contact with the pipe. This ultimately resulted in leaks, and in some cases, the concrete cracked longitudinally. One company has [143] developed a metal form which is put around the pipe above the trench. This is filled with concrete and removed a day later, when the concrete has set. This method makes it possible to use a relatively thin coating, thus reducing the cost. Concrete applied to pipe by means of steel forms was tested at site V of the API coating tests. Twenty feet of pipe beneath this coating was examined after 10 years. The maximum pit depth was 24 mils and the average on each 1 foot of pipe, 5 mils. The maximum pit depth on 10 feet of adjacent bare pipe was 50 mils and the average 38 mils. The 10-year-old API coatings examined in 1940 included 170 feet of asphalt emulsion shielded by cement mortar having an average thickness of 0.419 inch. Sixty-one 1-foot sections of the pipe beneath this coating were pitted. The depth of the deepest pit was 107 mils. It has been stated that the alkali in the concrete makes the pipe beneath it cathodic with respect to adjacent uncoated pipe and, therefore, accelerates the corrosion of the bare pipe.

The deepest pit on any of the uncoated pipe at site V was 65 mils and the average of the deepest pits on 13 uncoated 8-foot sections was 49 mils. These data do not support the theory that the coating accelerates the corrosion of adjacent bare pipe. If such a phenomenon should exist, it could be overcome by the use of insulating joints at the ends of the coated sections or the application of an insulating coating, such as coal-tar enamel, to a few feet of the line adjacent to the cement coating. Another solution would be the application of the coating to the entire line. It will be noted that the concrete was not sufficiently alkaline to prevent corrosion of the metal beneath it.

Occasionally, a condition occurs where it is not convenient to remove the pipe from the trench for the application of a bituminous coating or where the weather is such that it is difficult to keep the pipe dry over a sufficient period to permit the application of a hot bituminous coating. In such a case, or if local labor unfamiliar with handling bituminous coatings has to be employed, concrete may be the best coating to use.

(b) GREASE COATINGS

Grease with or without an added inhibitor, such as a chromate, has been used extensively by several pipe line operators. Usually the grease is protected by a coat of wax or by a wrapper of fabric or metal foil. Greases have the advantages that they can be applied cold by hand to a pipe which is not dry and that they tend to flow and so to heal any small openings in the coating. They have been used successfully under wet soil conditions. Bredberg [144] has written an interesting description of such an application of grease.

(c) BITUMINOUS COATINGS

The various kinds of bituminous coatings can be divided into two general groups—asphalt base and coal tar base. Each base has certain characteristics that make it preferable to the other, but each has some characteristics that are objectionable. Within each group, the materials vary so greatly that it cannot be said that one base material is superior to the other. In general, the asphalt-base materials are less susceptible to shock and changes in temperature, but they tend to change more and to absorb or transmit more moisture than the coal-tar-base materials. The so-called plasticised coal-tar enamels are more nearly like the asphalts in their response to changes in temperature, but the range of temperatures within which they can be successfully applied is smaller than that of the older enamels.

The fundamental requirements of a satisfactory bituminous coating are permanence, continuity, and low electric conductance, but certain other characteristics are necessary for a satisfactory coating. The hardness or softening point, as measured by standard ASTM methods, should be as high as is consistent with freedom from cracking and satisfactory application, and this will depend on the character of the bitumen, the method of application, and the season and the locality where the coating is applied or used. Continuity depends mostly on the care with which the coating is applied to the pipe, but ultimately it will be affected by the resistance of the coating to cracking and cold flow under pressure.

Many bituminous coatings have a high coefficient of expansion and should be protected against large rapid changes in temperature. High dielectric strength, that is, ability to withstand high electric potentials, is not in itself important, but the coating should have a low conductance or high resistance to low potentials. The fact that a coating when applied to a pipe will withstand several thousand volts has little significance except as an indication that the area tested is free from pinholes. Measurement of electric resistance after exposure to water for several months is a better test.

Adhesion of the coating to the pipe has often been stressed. Its importance lies in the fact that if the coating does not adhere, water entering at one point will spread beneath the coating, and the resulting corrosion may lift the coating and expose still more pipe to corrosion.

Probably the best way to secure continuity and long life for a bituminous coating is to use multiple applications. If a reinforcement is used to obtain thickness, it should be of inorganic material. It has been shown that organic fabrics exposed to moisture may rot. A stiff permanent wrapper will distribute the pressure on the coating and reduce distortion. A light bitumen-saturated asbestos-felt wrapper is not sufficiently rigid to prevent distortion of soft bituminous coating and may be penetrated by grass roots. Figure 73A, shows a root that has penetrated an asphalt coating reinforced by two layers of rag felt. Figure 73B, shows grass

roots in an asbestos-felt wrapper applied to a coal-tar enamel. These figures are of interest because they indicate that sufficient moisture to permit plant growth penetrated the bitumen-saturated wrappers. Figure 3 shows the distortion of a rag-felt-reinforced asphalt coating exposed to a heavy clay soil that cracked on drying. The figure also shows cracks in the coating, which may be the result of soil movement or of deterioration of the bitumen. Figure 76 shows a cotton-fabric-reinforced-asphalt coating that cracked badly, probably because of evaporation of volatile constitutents. In the same figure is shown a coal-tar-pitch coating that flowed from the top of the pipe. The resulting corrosion was much more severe than on nearby uncoated pipe.

FIGURE 76.—*Examples of failure of pipe coatings.*
A, Cotton fabric reinforced asphalt coating—note cracks; *B*, a coal-tar coated pipe from which the coatings flowed because it was too soft. Soil—tidal marsh.

Any specification for bituminous coatings should include a high-voltage test of the bitumen before reinforcement or wrapper is applied to the coating, if this is practicable. Care should be taken that every part of the coating is brought into intimate contact with the brush or other terminal of the high-voltage circuit. If the pipe has been transported after coating, it is advisable to test the coating again just before it is placed in the trench. Great care should be taken to see that the bottom of the trench is free from stones and foreign material and that such materials are not allowed to come in contact with the coating when the trench is back-filled. Care should also be taken to see that the coating is not injured by skids, chains, or other tools used in laying the pipe, as faulty application and accidental injuries are the most common causes of coating failures.

An inspection of the coating by means of the Pearson [137] apparatus a year or so after the pipe is laid will show whether or not the coating

has been properly applied and handled. Subsequent inspections by the same method will indicate the progress of coating deterioration, if any.

The American Water Works Association [145] has prepared specifications for coal-tar enamels for use under different conditions. They are not suitable, however, for coal-tar enamels of the older types or for asphalt-base coatings. The tests include softening point, percentage and fineness of filler, specific gravity, penetration, high-temperature, low-temperature, and impact tests. Only experience will show whether or not the use of these specifications will insure a good coating material, but they are certainly a step in the right direction.

It frequently has been said that as a result of the API tests great improvements in pipe coatings were made. It is of interest, therefore, to consider the type of coating selected by the War Emergency Pipe Line [146], an organization composed of prominent pipe line operators, for the most important pipe line in the United States. Most of this line received a coat of coal-tar primer followed by a coat of coal-tar enamel and a wrapper or shield of asbestos felt. The coatings were machine applied at the right-of-way and have an average thickness of $\frac{3}{32}$ inch. Most of the line was not electrically tested for pinholes. The reason for the choice of this type of coating is not entirely clear, but it may have been influenced by the exigencies of the situation—availability of materials and machines, ease of application, etc. Whether or not the choice was a wise one will not be known for a decade or more. The Products Line [147] constructed by the same organization, was similarly protected. However, it was triple-coated and wrapped at river crossings. In the wet, corrosive soils of the Gulf Coast area, some of the feeder lines were coated with an asphalt mastic coating similar to coating O in the API tests but which was applied by a somewhat different machine, which extruded the mastic around the pipe without seams.

As previously noted, one company protects its 6-inch gasoline lines by enclosing the sections exposed to corrosive soils in a cypress box with a 2-inch space between its sides and the pipe. The pipe is supported by porcelain blocks. The box is lined with roofing paper and filled with asphalt. The expenses of this treatment of short sections of pipe is thought to be less than cathodic protection, and is preferable because less attention is required.

Another large pipe line operator [148] uses a petroleum asphalt applied at the site by machine and shielded by a spiral wrap of asbestos felt. The thickness of the coating is $\frac{3}{32}$ inch. Sterling [148] reported that after 13 years a pipe coated with asphalt and asbestos felt was in excellent condition, whereas unwrapped sections of this pipe were almost beyond recovery, many joints having from 15 to 18 penetrations.

Thomas [149], who for many years has taken a leading part in the development of the pipe coatings in Australia, reports that the following coating has been adopted for the protection of large-diameter water pipes in Melbourne:

Pitch, vertical retort, gasworks; softening point 170° to 180° F.	34%
Tar, horizontal retort, gasworks, crude	26%
Limestone (200 mesh)	20%
Steatite (200 mesh)	14%
Asbestine	6%

Melting point of enamel, ring and ball, 175° F.

Working temperature for application, 450° to 500° F.

It may be noted that the percentage of filler is higher than that ordinarily used in the United States and that much of it is limestone. Most specifications in this country require an inert filler, and some prohibit the use of calcium carbonate and slacked lime. Rag felt is used as a shield because asbestos felt is not manufactured in Australia.

Elaborate apparatus has been developed for the application of the enamel to the inside and outside of pipes. For the outside coating, two layers of enamel are applied after which they are spark tested, a layer of rag felt is then applied and flooded with a third coat of enamel. Finally, the coating is whitewashed. The thickness of the coating is 0.24 inch. The interior coating is spun on to a thickness of 0.1 inch.

Apparently, asphalt is preferred in Holland, as the Dutch Corrosion Committee [3] has issued detailed specifications for the testing and application of asphalt coatings in several thicknesses. Kieselguhr, clay, gypsum, or other water-soluble salts must not be used as fillers. Asphalt-saturated wool felt and impregnated jute are specified as reinforcing materials. Four degrees of protection are specified—

1. Light protection (not to be applied to steel pipes):
   A. A coat of blown asphalt.
   B. A wrapping of waterproof paper to protect the coating against damage during transport and laying.
2. Moderate protection:
   A. Priming coat of blown asphalt.
   B. Topcoat of filled asphalt with or without a protective wrapper.
3. Heavy protection:
   A. Priming coat.
   B. Topcoat of filled asphalt.
   C. Reinforcement—jute or wool felt.
   D. Protective coat of filled asphalt.
4. Very heavy protection:
   A. Priming coat.
   B. Topcoat of filled asphalt.
   C. Reinforcement; impregnated coir cloth or impregnated asbestos felt.
   D. Protective coat of filled asphalt.
   E. Paper wrapping.
   F. Straw cord wrapping.

Little information has appeared as to the effectiveness of the newer pipe coatings, partly because a decade or so must elapse under most soil conditions before corrosion becomes serious even on poorly coated pipe, and partly because sponsors of coatings are averse to the publication of results that do not meet their expectations. Furthermore, the shortage of manpower has prevented any inspections of coatings that could be postponed.

Rogers [150] has reported some data on new enamel coatings. One coating consisting of an enamel and asbestos-felt wrapper showed a resistance of from 400 to 9,000 ohms per linear foot of pipe after 2 years, and changed little during the next 2 years. A second machine-applied enamel shielded with asbestos felt and applied in 1940 had an initial resistance of 67,500 ohms per foot. After 14 months the resistance ranged between 375 and 11,000 ohms per foot. Another machine-applied enamel showed nearly a uniform resistance of 6,200 ohms per foot after 14½ months. The same materials, hand-applied to another section of line, showed resistances ranging between 3,875 and about 200 ohms per foot

after 15 months of exposure. Three interesting facts are shown by the data. During the first few months after burial one 4,000 foot section of one coating dropped from a very high value of resistance to a minimum of 400 ohms per foot. After the initial drop in resistance the coating showed little change in resistance. The resistance of the coatings differed greatly at different sections of the line.

Similar data were reported by Hadley [151]. A section of an 8-inch steel line laid in a dumping ground was protected by three coats of coal-tar enamel, shielded by wrappers of asbestos felt and kraft paper, machine applied. The thickness of the coating was $5/16$ inch. The line was divided into 2,000-foot sections by insulating joints. Extreme precautions were taken to insure a perfect coating and high insulating joint resistance. To prevent injury by the back-fill, the pipe was surrounded by a layer of sand. Test wires were brought out from each section of the pipe. When installed the average resistance of the coating on 14,300 feet of the pipe was 94,000 ohms per linear foot. At the end of 3.8 years the average resistance of the same sections was 9,300 ohms per foot. Initially, the maximum resistance of one 2,000 foot section was 429,000 ohms per foot. The final resistance of this section was 2,600 ohms per foot. One section had a resistance of 536 ohms per foot after 3.8 years. Most of the changes in resistance occurred between the third and the ninth month of exposure.

At the 1944 convention of the National Association of Corrosion Engineers, Hugo [152], in describing the use of the Pearson coating-tester, reported that an inspection of about 150 miles of an asphalt mastic coating, most of which was about 1 year old but with 11 miles of $3\frac{2}{3}$-year-old coating, disclosed 80 electrical imperfections. Eleven of these were examined and five obvious coating injuries were found. At six points the imperfections were not visible. A similar test of 45 miles of asbestos-felt-shielded coal-tar-enamel coating of about the same age revealed 36 electrical leaks, 3 of which were examined. One defect was a large holiday beneath the wrapping; the second was a puncture of the coating by a ring from the pipe left in the trench; the third was a defective patch with the water beneath it. It will be noted that all of these failures were the results of poor inspection rather than of poor coating materials.

McCabe and Hull [153] reported that a test of 35,000 feet of 7-inch mastic-coated pipe showed an average resistance to ground of 500,000 ohms per linear foot about 6 months after it was placed in the ground. This may not have been a sufficiently long exposure to allow the coating to reach its minimum resistance.

As no one type of coating is superior to all others under all conditions, it is usually best to choose the type that can be most easily applied under the circumstances, because poor application is one of the chief causes of unsatisfactory performance.

XIV. CATHODIC PROTECTION

Until comparatively recently, the methods discussed in the preceding sections were the ones commonly employed for the prevention or mitigation of underground corrosion. More recently, however, the method known as cathodic protection has been applied, and its use is growing rapidly in practice. Fundamentally, cathodic protection consists in impressing electromotive forces on an underground structure through auxiliary anodes in such a way as to make the entire structure cathodic with respect to the adjacent soil. Although this procedure does not eliminate

corrosion, it transfers the corrosion from the protected structure to the auxiliary anodes, which are more easily and economically replaceable. This method does not prevent direct chemical attack, which is ordinarily negligible.

The use of zinc as an anode for the protection of ship bottoms, boilers, and similar structure has been practiced with varying degrees of success for many years. Also, a system of cathodic protection known as "pipe drainage" [19] has been used to protect pipe lines from corrosion due to stray currents from street railway systems. The beneficial effects were not fully appreciated, however, until the street railways were abandoned. In 1932, Scherer [154] reported that 26 companies were operating 542 cathodic protection units to protect 2,006 miles of pipe. Since that time, the number of miles of pipe so protected has considerably increased.

1. GENERAL PRINCIPLES

Theoretically, it should be possible to stop electrolytic corrosion by bringing the buried metal to such a potential with respect to the adjacent soil that no current flows out of the surface of the metal. Practically, however, neither the metal nor the soil can be made an equipotential surface and current will leave certain elements of the surface of the metal even though the average value of the current is zero. In order for all parts of the metal surface to be cathodic, therefore, the applied voltage must be great enough to cause a certain amount of current to flow into the protected metal surface. From the economic point of view, the current should be no greater than the minimum necessary to afford complete protection. Excessive current involves an unnecessary expenditure of energy and excessive consumption of anode material. The latter loss might be avoided by the use of noncorrodible anodes but this is generally not feasible.

2. CRITERIA OF PROTECTION

The most difficult problem in connection with the application of cathodic protection is that of determining whether or not protection is actually effected. Obviously, the determination must be made indirectly because it is not possible to make direct observations of corrosion, and it would not be satisfactory to wait several years after the application of cathodic protection in order to determine by inspection whether or not it has been effective. Consequently, it has been necessary to adopt certain arbitrary empirical criteria, based for the most part upon experience, for judging whether or not the cathodic protection is adequate. The principal criteria in common use are based either upon estimates of the current density at the surface of the protected material or upon measurements of the potential of the protected material with respect to that of the soil. A third criterion that has been investigated is the relationship between the potential of the surface to be protected and the current flowing into it as the applied electromotive force is increased or decreased.

(a) CURRENT DENSITY

Of the three criteria mentioned, current density at the protected surface is the least satisfactory for two reasons. (1) the value must be calculated as an average over a comparatively large area over which the distribution of the current is normally far from uniform, and (2) no simple way has been found for determining the value of the current density necessary in a given case. Furthermore, conditions are likely

to change with time, so that the value of the current density necessary for protection may not be the same at different times.

The difficulty in determining the value of current density required for complete protection is apparent from the values given by different investigators. The values reported range from 1 to 15 milliamperes per square foot. Rhodes [155] found the minimum effective current density to be about 20 microamperes per square inch, or about 3 milliamperes per square foot, whereas Hill [156] from laboratory experiments concluded that the protective current density ranged from 1 to 10 milliamperes per square foot.

Rogers [157] reported that in one soil a current density of 3.65 milliamperes per square foot reduced the corrosion loss by 98 percent whereas in another soil a current density of 8.2 milliamperes per square foot reduced the loss only 82 percent. Keeling [158] found that a current density of 15 milliamperes per square foot was required to protect submarine pipe lines. Ewing [93] found that from 1.5 to 14 milliamperes per square foot was required to protect different sections of pipe in Louisiana and Texas.

A further complication arises if cathodic protection is to be applied to a pipe line on which there is a protective coating. Obviously, the current required would depend upon the number and size of the apertures in the coating. For instance, one operator found that the current required to protect a coated line was about 4 percent of that required for the protection of an uncoated line.

It appears from the experiences and opinions cited above that current density is not a safe criterion for determining whether or not cathodic protection is adequate in a particular case.

(b) PIPE-TO-SOIL POTENTIAL

The purpose of cathodic protection is to prevent corrosion by making all points on the surface of the metal cathodic with respect to the adjacent soil. However, as the surface of the metal can not be made an equipotential surface, it is difficult to tell by any practical method whether or not the desired condition has been produced. On account of this uncertainty it is customary to make an allowance of from 0.2 to 0.3 volt to provide for inaccuracies of measurement and variations in service conditions.

The polarity of the metal with respect to the soil is usually determined by means of a high-resistance voltmeter, potentiometer-voltmeter or vacuum-tube voltmeter, and a steel or copper sulfate electrode. Some engineers follow the method of Rhodes [159] and use an electrode of pipe steel placed about ⅛ inch above the surface of the pipe. Values obtained by this method are said to be reproducible to about 0.02 volt. Sufficient current is applied to the pipe to make its potential 0.2 volt below that of the electrode. Other engineers [160-164] use a copper sulfate electrode placed above the pipe and assume that the normal potential difference between such an electrode and a pipe that is neither collecting nor discharging current is 0.54 volt [160]. They usually assume that the pipe is protected if its potential is lowered to —0.80 or —0.85 volt with respect to the copper sulfate electrode.

Records of leaks on one corroding pipe after cathodic protection has been applied and maintained for some time indicate quite definitely, at least under most soil conditions, that keeping the potential of the pipe line at least 0.85 volt below that of an adjacent copper sulfate electrode will prevent additional leaks after the protection has become established.

Many corrosion engineers feel, therefore, that this is a sufficiently good criterion for practical purposes, especially since the measurements can be made easily and quickly. However, if the pipe has a high-resistance coating with only small holes or cracks, this criterion may fail on account of the high IR drop involved in such cases.

There are several objections to the use of potential difference as a criterion of protection. Kuhn [165] has shown by an extended series of tests that the potential of cast iron with respect to a remote reference electrode varies from point to point. He also reported that the potential of the pipe as a whole changed with the time the pipe was in the earth. Gatty and Spooner [90] have shown that increasing the supply of oxygen raises the potential of iron in an electrolyte and that increasing the alkalinity of the solution lowers the potential of the iron. As soils differ widely in oxygen and alkali concentrations, they should also differ with respect to the soil-iron potentials.

That the potential of iron with respect to a copper sulfate reference electrode is not the same for all soils is indicated by the following tabulation. For a test of the effectiveness of zinc as a source of cathodic protection, three iron rings were buried in each of eight locations. The potential of each ring was measured with a potentiometer-voltmeter before the experiment was started. The potentials at six of the test sites are shown below:

Location	Potential of iron ring with respect to $CuSO_4$ electrode *Volts*
Austintown, Ohio	−0.575 to −0.600
Deerfield, Ohio	−.725 to −.730
Rocky Ford, Colo.	−.740
Albuquerque, N. M.	−.70 to −.74
Los Angeles, Calif.	−.49 to −.52
Shreveport, La.	−.753 to −.760

These differences in potential may be accounted for in part by different percentages of anodic areas, as they are the resultants of the potentials of the anodes and cathodes on the surface of the iron.

The potential difference between a pipe and an electrode some distance from its surface may be affected by an IR drop caused by current flowing to or from the pipe or by other currents in the earth. This may be important in cases of cathodic protection. On account of the possible sources of error just mentioned, many engineers use the change in potential of the pipe when current is applied as the criterion for the degree of protection and assume that the pipe is protected when its potential has been lowered 0.3 volt. Obviously, the condition of the pipe may be such that no current is required for its protection, in which case the lowering of its potential is unnecessary. Under other conditions the change in potential of the pipe with respect to an electrode some distance away may be due largely to the IR drop in the soil and not representative of the change at the pipe surface. To avoid this error some engineers use an electrode separated from the pipe by only about ⅛ inch of insulation. This avoids most of the IR drop unless the pipe has an insulating coating, but such measurements are influenced by the condition of the pipe adjoining the electrode. It is, of course, possible to take account of the resistance of the soil or coating surrounding the pipe, as has been done by Ewing [164] and Scott [166, 167]. The most important objection to potential or change in potential as a criterion for protection was pointed out by Ewing [93], who showed that when current was applied to a cathode such as a pipe line, the potential of the protected metal with

respect to a reference electrode might gradually increase or decrease, depending on the reaction at the cathode. The reaction is determined by the aeration and pH value of the soil.

(c) CURRENT-POTENTIAL CURVES

In the course of a study of the velocity of corrosion Britton [92] found that when the current flowing to a piece of iron in aerated 1/10 *N* potassium chloride solution was gradually reduced from a value more than sufficient to prevent corrosion of the iron, the potential of the iron with respect to a reference electrode quite near it increased up to a certain value and then remained constant as the current was further reduced. Experiments as well as theoretical considerations showed that the break in the curve occurred at the current density just sufficient to prevent corrosion. The experiment was repeated with other concentrations of potassium sulfate. The explanation of the horizontal part of the curves, where there was no change in potential of the cathode with increasing current, is that the truly cathodic areas were large compared with the corroding areas and so determined the measured potential. This potential did not change because all the current entered the anodic areas. It was used in counteracting the local or corrosion current from the anodes. This unequal distribution of current may be explained by the assumption that the cathodic area was insulated by a relatively high resistance film.

If the corrosion is not controlled by the cathode, the current potential curve may not have a horizontal part or even a critical point. However, the corrosion of iron is usually controlled by polarization of the cathodic areas.

Ewing [93], working at the National Bureau of Standards as a Research Associate for the American Gas Association, undertook an extended investigation to determine how the phenomenon discovered by Britton could be used to determine the current required for the protection of pipe lines. Müller [89] showed that the measured potential of a corroding cathode was its true potential diminished by the IR drops resulting from the flow of the local and imposed currents, i.e., that if these IR drops were deducted or eliminated from the observed values, the true value would be obtained. Ewing also showed by reasoning and citations of the work of other experimenters [168] that after the current became sufficient to prevent corrosion, the cathode would act as a hydrogen electrode and that the potential of such an electrode varied linearly with the logarithm of the current flowing to the cathode. Consequently, if the true potential of the cathode is plotted against the logarithm of the impressed current, the resultant curve should consist of horizontal and sloping lines connected by a curve representing the transition to the overvoltage curve, as shown in figure 77. The intersection of the projections of the straight lines is taken to indicate the current required to prevent corrosion. If the resistance of the electrolyte is low, sharp breaks in the current-potential curves can be obtained without correcting for the IR drop, as was done by Britton. With high-resistance electrolytes, however, a smooth curve with no break is obtained (see fig. 79) if the potential is not corrected for IR drop. A laboratory method for obtaining data for current potential curves free from IR drop has been described by Pearson [169]. His apparatus was simplified and made applicable to field work by Hadley [170] and associates. Figure 78 shows the essential features of the Pearson-Hadley circuit. At the top of the figure is a source of variable current, consisting of a battery and resis-

tance connected through an ammeter and rheostat between an anode and the pipe to be protected. The remainder of the circuit consists of two copper sulfate electrodes, $E+$ and $E-$, a high-resistance null indicator, V, preferably a vacuum-tube voltmeter, a potentiometer-rheostat, R_3, and a potentiometer voltmeter, referred to later as a back-out circuit. The operation of the apparatus is as follows: With the battery circuit open and switch S_2 in the down position, the potential of the pipe with respect to electrode $E-$ is obtained by applying a counter-potential by the backing-out apparatus R_2, until indicator V reads zero. (If V is a calibrated vacuum-tube voltmeter, it will indicate the potential if the backing-out potential is set at zero.) S_2 is then reversed, the current cir-

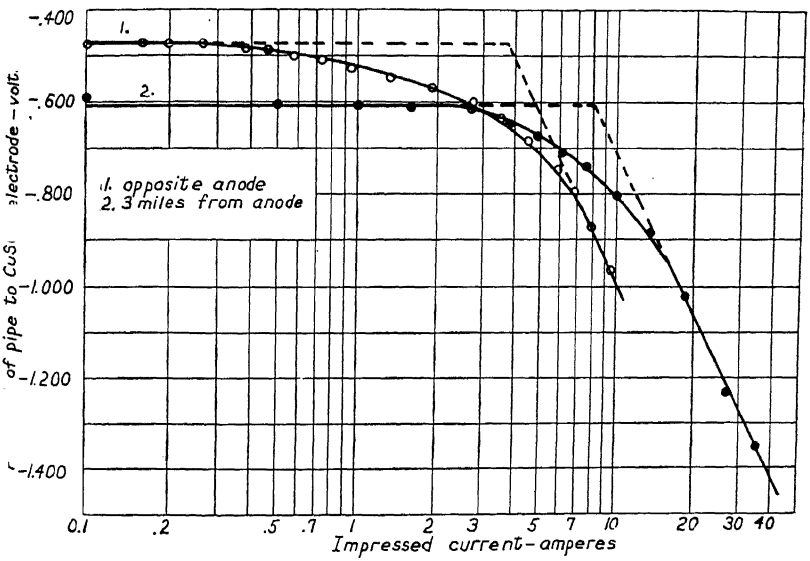

FIGURE 77.—*Current-potential curves for 6-inch pipe.*

cuit closed, and rheostat R_1 adjusted to permit the passage of the estimated protective current or any other current sufficient to cause a well-defined change in the reading of the vacuum-tube voltmeter when switch S_1 is shifted. The switch is then moved from side to side, thus changing the current, and the sliding contact, N, on the null potentiometer, R_3, is adjusted until changing the position of switch S_1 causes little or no change in the reading of the vacuum-tube voltmeter. When a change in current does not affect the deflection of the voltmeter, the IR drops in the earth are just balanced by the corresponding IR drop in the null potentiometer, and their effect is eliminated from the result.

A comparison of the null circuit, 1, with the Wheatstone bridge circuit, 2, and the equivalent null bridge circuit, 3, in figure 78, in which corresponding points have been similarly lettered, may make the operation of the circuit clearer. The batteries in the null bridge circuit represent the voltage supplied by the backing-out potentiometer and the potential of the pipe with respect to the reference electrode. If the bridge is first balanced with respect to resistances (IR drops), the galvanometer, V, will read zero when the backing-out voltage equals the potential of the pipe. It is advisable to make the positions of $E-$ and $E+$ such that

a balance is obtained when the contact, N, is somewhere near the center of R_3 since the apparatus is most sensitive to changes in I under this condition.

When the bridge or null circuit has been balanced for a current high enough to give a reasonable sensitivity, the current is reduced to a very small value. After sufficient time has elapsed for the vacuum-tube voltmeter to reach a steady state, the potential across it is backed out by

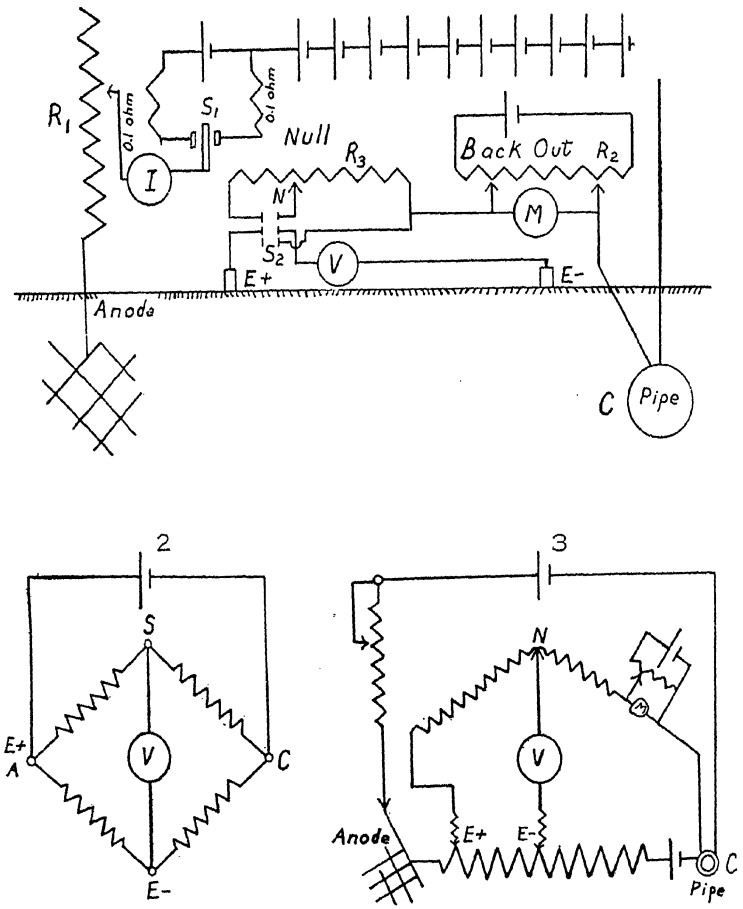

FIGURE 78.—*Pearson-Hadley null current.*

1, Null circuit; 2, wheatstone bridge current for comparison with 3, the testing circuit in 1. The letters designate corresponding parts in each circuit.

means of the potentiometer resistor, R_2, and the readings of the ammeter, I, and the voltmeter, M, are recorded. Rheostat R_1 is then readjusted to pass from 30 to 50 percent more current and a new balance is obtained. Thus a series of observations of potential and current are accumulated. At first, little or no change of potential will be observed. Observations should be continued until four or more definite changes in potential have been observed.

Usually, it will not be necessary to readjust the null circuit until after the critical current has been passed. In some cases, the circuit becomes badly unbalanced for large currents. It is advisable, however, to check the balance of the null circuit from time to time. The data for figure 77 were obtained by Hadley on a 6-inch pipe. The apparatus used in obtaining the data for curve 1 was set up near the point where the power was connected to the pipe, but the anode was about a quarter of a mile from the pipe and the positive copper sulfate electrode about 125 feet from the pipe. A welding generator supplied the current.

The voltage data for curve 2, figure 77, are for a point on the same pipe about 3 miles from the power connection. The welding generator, ammeter, and control rheostat were at the same place in each test. In the second test, communication was by radio, but a modification of Smith's communication system described in Ewing's book [29], under the topic "Measurement of Network Constants," could have been used. The negative copper sulfate electrode was placed over the pipe and the positive electrode was about 90 feet from the pipe. Curve 2 is presented to show that the null method can be used to obtain data at points remote from the power connection.

The potential-log current curve consists of but two straight lines only when little or no current flows to the cathodic areas on the pipe while anodic areas remain. This condition obtains when the corrosion is cathodically controlled, i.e., where corrosion products on the cathode determine the rate of corrosion either by their resistance or potential. If cathodic control is incomplete, the curve for low current densities will not be horizontal but have a slope. If the cathodic control fails gradually, the potential-log current curve will bend. Bending will also occur if the potential readings contain an IR drop. For this reason, it is important to maintain the balance of the null circuit.

That part of the polarization potential that is the result of the accumulation of alkali at the cathode changes gradually and persists for a considerable period after the current has been cut off. Because of this type of polarization, observations of current and potential must be made at equally spaced time intervals if a smooth curve is to be obtained. Two or three minutes is a good interval, which allows sufficient time for the adjusting of apparatus and occasional checks of the null circuit. This persistence of polarization accounts for the fact that the operator cannot drop back to a lower current to check an observation in the course of a test and also for the fact that the potential at zero current after the test will not be the same as initially. Successive tests within a few hours of each other will often show small decreases in the protective current for the same reason.

Tests run with the initial current either at the maximum or at the minimum value will give substantially the same value for the protective current, but the potential for zero current after a test will be lower than the original potential of the pipe. For this reason the potential of the pipe should be measured before any current is applied.

The laboratory tests upon which the above method of determining the protective current is based were performed with small electrodes in a uniform electrolyte. It might be asked whether or not they are applicable to pipe line along which the the potential varies. Pearson [171] has pointed out that 90 percent of the observed potential of a line with reference to an electrode at the surface of the ground is contributed by a segment four times as long as the distance from the pipe to the electrode.

An electrode placed over a line 30 inches deep, therefore, is affected by the potential of about 10 feet of the line and is only slightly affected by the remainder of the line. To determine the current required to protect this part of the line, it is necessary to measure the current in the pipe on either side of the segment and so compute the current collected by the segment under observation. The fact that, with care and adequate apparatus, log current-potential curves with reasonably sharp critical points can be obtained indicates that the laboratory test is applicable to field conditions.

Under some conditions, the potential-log current curve consists of three or more parts. The work of Gatty and Spooner [90] suggests that if the cathode has been exposed to oxygen, the first change in the slope of the curve represents a reduction of the oxides on the cathode. When this reduction is complete, the hydrogen-overvoltage curve follows. If the current density is increased sufficiently, the curve may again depart from its previous course.

Some unpublished work by Denison suggests that the true protective current is indicated by the point where the potential curve first begins to bend rather than by the intersection of the horizontal and the hydrogen over-voltage lines, and this is in line with Miller's unpublished opinion that the latter point sometimes indicates a current greater than that necessary for protection.

(d) COMPARISON OF RESULTS OF DIFFERENT METHODS FOR DETERMINING THE PROTECTIVE CURRENT

As the apparatus required for the Pearson-Hadley method for determining the current required for the protection of a buried structure is obviously more complicated than that in common use, and since the time required for the tests is longer, it is of interest to consider whether or not the different methods give similar results, as well as to consider the evidence for their validity.

Figure 79 shows current-potential curves taken in several ways. The cathode was a buried tank with 8- by 12-inch steel plates placed about 8 inches from the tank near the top, middle and bottom. The sides of the tank were coated with coal-tar enamel.

Curves 1, 2, and 3 show the potential of the tank with relation to the steel reference electrodes near the top, center and bottom of the tank, respectively. It will be noted that the tank is at nearly the same potential with repect to the top and bottom electrodes, and that there is a difference of potential of nearly 0.3 volt between the top and middle electrodes.

If the tank is protected when its potential is 0.3 volt below that of the reference electrode, 1.3 amperes are required for protection, according to the indication of the central electrode, while the other electrodes indicate that no current is required. If a change in potential of 0.3 volt with respect to a steel electrode is the criterion, the required currents are 1.4, 1.5, and 1.9 amperes for the top, center, and bottom electrodes, respectively.

If a copper sulfate electrode is the reference point, curve 4 indicates that 0.32 ampere is the protective current on the basis of a potential difference of 0.85 volt and 1.3 amperes on the basis of lowering the potential 0.3 volt. If the null method is used, curve 6 indicates that a current of 0.7 ampere is required for protection. Other curves obtained by the null method indicated that the protective current was 1.0, 1.1, and 1.2 amperes.

For the tank under discussion it appears that the change of 0.3 volt and the null method give about the same results within the limits of reproduction. Changing soil and electrode conditions made it impossible to determine a single value of current which will just furnish protection at all times so far as the tank in question is concerned, and prob-

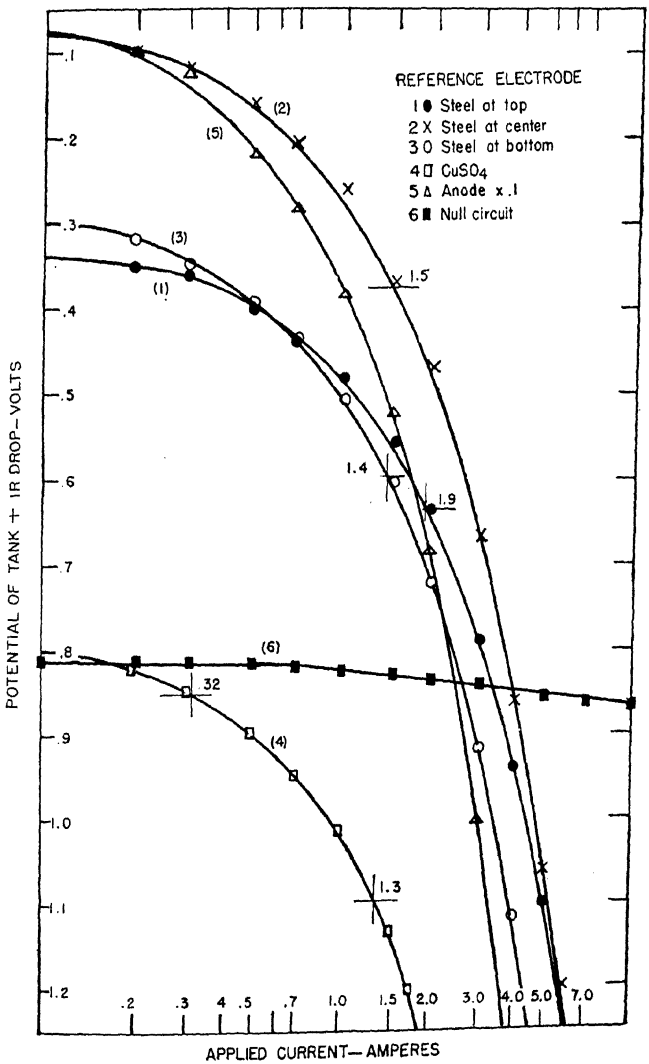

FIGURE 79.—*Current-potential curves for a buried tank.*

ably an engineer would have chosen about the same value for the protective current for the tank whatever his criterion.

Similar conclusions do not always result from such comparisons of methods. Figure 80 shows the results of two tests run simultaneously by Hadley and others on a 40-foot section of bare 16-inch steel pipe that was separated from the remainder of the line by Dresser coupling. The

upper curve was obtained by the null method. It indicates that 3 amperes are required to protect the section. A similar test run a few hours earlier indicated 2.5 amperes were required for protection. The lower curve was obtained by the usual method, using a potentiometer voltmeter and a steel electrode placed 1/8 inch above the pipe and a foot to one side of the copper sulfate electrode used for the null method. The curve indicates that 18 amperes are required to lower the potential of the pipe 0.3 volt. A third simultaneous test employing another steel electrode 1 foot on the other side of the $CuSO_4$ electrode indicated that 30 amperes were required to lower the potential of the pipe 0.3 volt. A protective system installed by a consulting engineer was furnishing 0.1 ampere for the protection of this section.

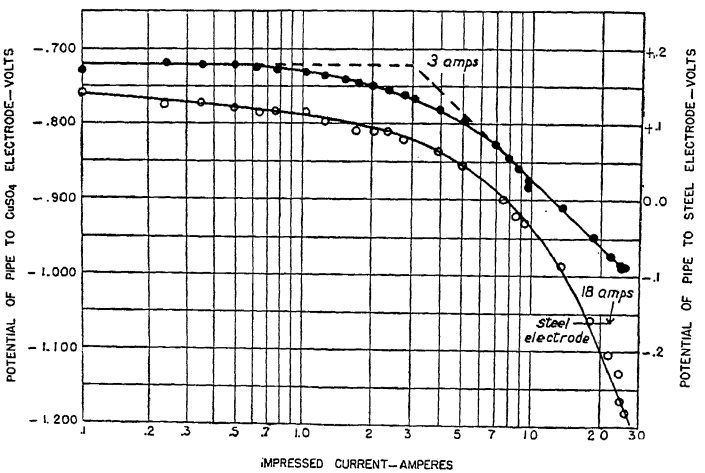

FIGURE 80.—*Current-potential curves for 40 feet of 16-inch pipe.*

When a pipe line is made cathodic, two changes occur at or near its surface. (1) There is polarization resulting usually from the deposition of hydrogen. Most of this change occurs within a few minutes and disappears within a short time after the current is cut off. (2) There is an accumulation of alkali near the surface of the pipe. This change increases with the flow of current until it is neutralized by the diffusion of the alkali into remote soil. The effect of the alkali persists to a decreasing extent for some time after the current is cut off. Because of these changes it is not possible to make the most economical adjustment of the protective current until the system has been in operation for some time. The current supplied by the source of power will be affected by the ever-changing resistances of the anode, cathode, and intervening soil, and a redetermination of the current required for protection should be made from time to time if the use of a minimum current is desired.

Obviously, the amount of current needed will depend on the exposed area of the pipe. For this reason, any insulating coating on the pipe tends to reduce the current necessary to complete the protection.

Complete protection depends on making every point on the surface of the pipe cathodic, that is, on making current flow to all points. Those familiar with the distribution of current over the surface of an electrode know that it is difficult to force current into or out of a narrow crack or depression. It follows that it will require more current to protect a

badly pitted pipe than one with a smooth surface. It is very difficult to protect a deeply pitted pipe. This accounts for the fact that many users of cathodic protection find that leaks do not stop for several months or years after protection is applied to a badly corroded line. This is illustrated in table 100, which shows the number of leaks that developed in protected section of pipe lines totaling approximately 36 miles [172]. The criterion for protection was a potential of 0.8 volt or more between the pipe and a copper sulfate electrode on the surface of the ground over the pipe.

TABLE 100.—*Effect of cathodic protection on rate of leak occurrence.*

Exposure period after application of cathodic protection	Number of leaks
Years	
1	130
2	242
3	17
4	8
5	7
6	6

Some of the leaks during the 2 years following the application of cathodic protection may be attributed to imperfect adjustment of the protection apparatus, and it may be that more current is required initially than later, but it seems probable that the continuous occurrence of leaks after protection was applied may be due to the fact that the protective current could not be forced into the bottom of the deep pits. When these were eliminated by their development into holes, which had to be repaired, the current was sufficient to protect the pipe.

3. CATHODIC PROTECTION INSTALLATIONS

(a) PROTECTION OF TRANSMISSION PIPE LINES

(1) *Principles.*—Fundamentally all that is required for cathodic protection is a source of direct current and a means of getting the current into the earth and off of the pipe to be protected. Cathodic protection engineering consists in determining how much current is required and selecting the most economical means for supplying and distributing the current. In general, two systems of current distribution are used, regardless of the source of the current. One system introduces the current into the earth at a single favorable location, and attempts thereby to protect as much pipe as is practicable. The current density at the surface of the pipe and the potential of the earth with respect to the pipe is greatest near the point where the current is removed from the pipe, which is usually the point on the pipe nearest the anode. The distribution of the current flowing to the pipe tends to become more nearly uniform and the amount of protected pipe tends to increase with increased separation between anode and pipe up to distances of a few hundred feet. This system requires the minimum wire to transmit current but is wasteful of current in the region near the anode. The distributed anode system, patented by Rhodes [155, 159, 173], requires less power but a greater investment in copper and power converters. For zinc as a source of current, the Rhodes system is almost essential, and for city networks it has certain advantages.

The design of cathodic protection for cross-country lines has been discussed by Rhodes [155], McGary [174], Rogers [175], Thayer [176],

Scott [167], Ewing [164], Schneider [177], and Olson [178]. Three main points have to be considered (1) an economical source of power including distribution costs and losses (2) a low-resistance anode, preferably with little polarization, low counter voltage or over-voltage and long life (3) as extensive a distribution of current from a single source as is consistent with economy, and with no interference with unprotected structures. Some of these requirements will be discussed in detail.

(2) *Sources of Current.*—(a) CONVERTED POWER. Windmills, gas-engine-driven generators, and rectifiers have been in use so long that their design has become stabilized, and to obtain satisfactory apparatus of these types it is only necessary to select a reliable manufacturer and furnish him information as to the current and voltage which are required.

Scherer estimated that in 1941 there were 750 cathodic units protecting 3,000 miles of pipe line. Approximately 45 percent of the total number of installations used rectifiers with outputs from 50 watts at 6 volts to 1 kilowatt at 20 volts. Their popularity is due in part to the fact that usually they contain no moving parts and require little attention other than an occasional adjustment of voltage. Single-phase copper oxide rectifiers have an efficiency of about 65 percent [179] and three-phase apparatus an efficiency of about 85 percent. Selenium and copper sulfide rectifiers have about the same efficiency. Electron-tube rectifiers are reported to be somewhat more efficient.

Gas-engine-driven generators are used frequently to protect gas lines, where gas to operate them can be taken from the line. Wind-driven generators furnish power for about 20 percent of the installations. Their popularity seems to be decreasing largely, because they have been installed where the wind is sufficiently continuous to be a satisfactory source of power. The velocity of the wind should not fall below 5 miles per hour for periods longer than a day, and the windmill should operate at least 75 percent of the time. The electrical and mechanical apparatus requires little attention. United States Weather Bureau reports are of value in a preliminary survey of wind possibilities in a given region but sometimes they are not applicable to the spot where a windmill is desired.

(b) PRIMARY POWER.—In sections of the country remote from power lines and unfavorable to wind-generated power, and in cities where the stringing of wires to supply current would be unsightly or expensive, and where anodes must be placed close to the protected structure to avoid endangering neighboring structures, the anodes themselves may be made to furnish current if the resistance of the soil is sufficiently low. Aluminum, magnesium, and zinc have been suggested because their potentials are less noble than steel.

A. ALUMINUM ANODES.—The electrode-potential series indicates that aluminum might be more effective than zinc as a current-generating anode for cathodic protection. Aliter [180] has reported an experiment in which he compared the effectiveness of the two metals for the protection of steel rods in two Hanford soils. His results indicated that the aluminum was more effective in a soil containing carbonates in which the zinc reversed its potential with respect to iron. Both the zinc and the aluminum contained iron as an impurity. As aluminum is attacked by some alkali soils, its use in such soils might be limited by local corrosion, although the pH of the Hanford soils was from 7.7 to 8.1.

B. MAGNESIUM ANODES.—The open-circuit potential between iron and magnesium is in the order of 1 volt, which is more than twice that

between zinc and iron. Olson [181] has reported some experimental work on magnesium anodes. Some of the anodes became inactive after a few months of exposure. Others continued to supply 50 percent or more of the original current. However, the loss of weight of the magnesium anodes was several times that attributable to the current supplied to the cathode (pipe). This investigation is being continued in an effort to find a magnesium anode less subject to local or galvanic corrosion. Grebe and McNulty [182] have reported extensive experiments with magnesium anodes, which show electrolytic corrosion efficiencies as high as 30 percent. They predict that future developments will make the use of magnesium anodes economically sound.

c. ZINC ANODES.—The open-circuit potential difference between iron and zinc is in the order of 0.4 volt, which may be enough to furnish an adequate protective current if the resistances of the soil and anode are low. Zinc anodes have been installed in a number of localities with beneficial effects, though in some cases the protection which they have furnished has not been complete. These failures to protect are in part attributable to an insufficient number of anodes and in part to improper installation or maintenance. Reports on zinc anodes have been published by Rhodes [159], Smith and Marshall [183], Brockschmidt [184] and Mudd [185]. Much of the work of these men and considerable additional information on zinc anodes has been summarized in a report by Wahlquist [186], from which much of the following paragraph was abstracted.

Zinc anodes were attached to a gas line in eastern Colorado in 1935. The first rods were 1 inch square and 4 feet long with a ¼-inch iron core, and each weighed 12 pounds. Later rods were round, with a diameter of 1⅜ inches, and each weighed 18 pounds. The rods were cast locally from electrolytic zinc. Usually eight rods, spaced about 10

FIGURE 81.—*Zinc carbonate formed from a zinc anode used to protect a pipe line.* The diameter is 1½ inch.

feet part, were connected together in a line parallel to the pipe line and from 5 to 14 feet from it. Most of the soils contained sulfates and carbonates and had resistivities between 700 and 200 ohm centimeters. Most of the installation furnished between 30 and 50 milliamperes per rod after from 6 to 8 years and maintained the pipe-to-soil potential at from −0.6 to −0.93 volt with respect to a remote copper sulfate electrode. Several leaks have occurred since the installation of the zinc anodes, but the frequency of their occurrence has been greatly reduced. The condition of the rods indicates that they will continue to furnish current until the zinc has been nearly consumed or until the iron core is exposed. The most common corrosion product is zinc carbonate, which remains in place around the rod as a moist solid cylinder. Figure 81 shows a section of such a carbonate cylinder pulled from an old rod. The wall thickness of the carbonate is ⅜ inch.

As a result of his experience, Mudd [185] uses a zinc anode rolled

from ¼-inch sheet zinc to form a cylinder 7 inches in diameter and 3 feet long. He places these cylinders in holes 8 inches in diameter and from 4 to 6 feet deep. Calcium-sulfate (gypsum) is placed around the cylinder, which is packed with crushed rock to expand the cylinder and make a good contact with the earth. Mudd found that his anodes were most effective when several were connected in parallel to give a total anode area of 30 square feet. He placed his nearest anode more than 100 anode diameters from the pipe and made the spacing between anodes 50 diameters, conforming to Schneider's [187] recommendations. Mudd's experience is not quite so favorable to zinc anodes as is that of Wahlquist [186].

Brockschmidt [184] connected ten 4 foot by 1⅜-inch zinc anodes in parallel at 5 foot intervals in a line 3 to 5 feet from an 18-inch Dresser-coupled enamel-coated gas line in the first bottom of the Mississippi River. Most of the soil had a resistivity in the neighborhood of 500 ohm-centimeter. After about 2½ years the average potential of the pipe was —0.198 volt with respect to a steel electrode in the soil a fraction of an inch distant, and —0.990 volt with respect to a remote copper sulfate electrode. After 449 days the total output of 10 electrodes was 110 milliamperes. The pipe was still positive to earth at one location.

The output of Brockschmidt's rods was less than half that of those in the Colorado installation, where the size and location of the rods and also the soil resistivities were approximately the same. Since the pipe-to-soil potentials were generally greater than the commonly accepted criterion of —0.85 volt for safety, the two installations may have been equally effective. Only the leak records will determine whether or not this is the case. The data presented as to the effectiveness of the two installations are unsatisfactory because they show only averages of widely variant data and because the criterion for effectiveness has not been established. There can be little doubt, however, that under many conditions zinc anodes properly installed and maintained will materially reduce corrosion losses.

Rhodes [159] and some others have stressed the importance of the use of very pure zinc for anodes. Others have not found this necessary. Additional research and experience will be necessary to determine the limitations of zinc anodes. Among the limiting factors are (1) low potentials, which limit their application to pipes in low-resistance soil, (2) local or galvanic corrosion, (3) the occasional development of high-resistance corrosion products, and (4) the reversal of potential (confined probably to impure zinc). As has been said, zinc anodes are almost necessarily placed close to the pipe, and as a result they have the advantage in city streets of not endangering adjacent unprotected structures. Another factor in their favor is the comparatively uniform pipe-to-soil potential resulting from the use of the distributed anode system.

(3) *Anodes* (a) Resistance to Earth.—In the preceding section, anodes have been discussed only as sources of potential. In the following section they will be treated as means of getting current into the earth. As such, their important characteristics are (1) resistance to the flow of current, i.e., electric resistance to earth, polarization, over-voltage, and counter electromotive force, (2) permanence, and (3) cost.

The resistance of the anode itself is usually negligible in comparison with that of the remainder of the electric circuit. Most of the resistance to the flow of the protective current is in the earth at or near the anode and cathode. If the cathode, the pipe to be protected, is bare, the resis-

tance at its surface is usually small and attributable to corrosion products or polarization. Making the resistance between anode and cathode low is one of the major problems of cathodic protection. This depends largely on the size, shape, and location of the anode.

Frequently, several anodes are connected together in a line parallel to the pipe to be protected, in which case they are known as distributed anodes, or in a two-dimensional group known as a ground bed. The distributed anodes usually consist of rods from 1 to 2 inches in diameter and 4 to 10 feet long. Eight or more are spaced from 5 to 10 feet apart in a line parallel to and a few feet from the pipe. The resistance to earth of the group is approximately that of the resistances to earth of the individual anodes in parallel, that is, $1/R=1/r_1+1/r_2+\ldots 1/r_n$, where R is the resultant resistance and r_1, r_2, etc. are the individual resistances to earth. The same equation applies to any other arrangement of anodes if they are sufficiently separated from each other.

The resistance to earth of the individual anodes depends on, but is not proportional to, their diameters and lengths and on the resistivity of the soils in which they are placed. The anodes may be placed vertically or horizontally, the choice depending largely on the depth of relatively low resistance soil. The data on the resistance to earth of ground rods for electric systems are applicable to anodes if they are placed in homogeneous soil. This subject has been discussed by Peters [188], but the additional resistance resulting from heating, osmosis, and polarization must be added.

Peters [188] showed that the resistance to earth of a pipe driven in the earth was represented by the equation $R=\varrho/2\pi C$, in which R is the resistance between the pipe and the earth, ϱ is the specific resistance of the soil, and C is the combined electrolitic capacity in free space of the electrode and its image above the surface of the ground. The value of C can be calculated approximately from the equation $C=2L/2 \log_e (4L/d)$, in which L is the length of the pipe and d its diameter. The equation can be used for computing the effect of increasing the diameter or length of the pipe. Figure 82 illustrates the effect of increasing the length of the pipe as determined by the above equation and by experiment in a high resistance soil.

Frequently, the resistance of the subsoil or underlying rock is so high that extending a ground rod into it does little good. It is advisable, therefore, to determine the resistivity of the soil at various depths by Gish and Rooney's [189] application of the Wenner method, as described earlier, and to limit the length of the anodes accordingly.

The effect of putting two or more vertical rods in parallel is illustrated in figures 83 and 84. The effect of the area of a plate near the surface of the earth on its resistance to earth is shown in figure 85.

If the subsoil has a high resistance, it may be advisable to lay the anode horizontally, in which case its resistance to ground will be $R=\varrho \log_e(2L/d)/\pi L$, in which the letters have the same significance as in the preceding equation.

If the resistivity of the soil is constant, the resistance to earth of a horizontal ground plate, such as a sheet of metal, decreases as its distance below the surface of the earth increases until, at depths large in comparison with the diameter of the plate, it is half that at the surface of the ground. The resistance to earth of a circular plate at the surface of the ground is $R=r/2d$, in which r is the resistivity of the soil and d is the diameter of the plate. Consequently, to reduce the resistance to earth of a plate to one-half, its area must be made four times as great. It would

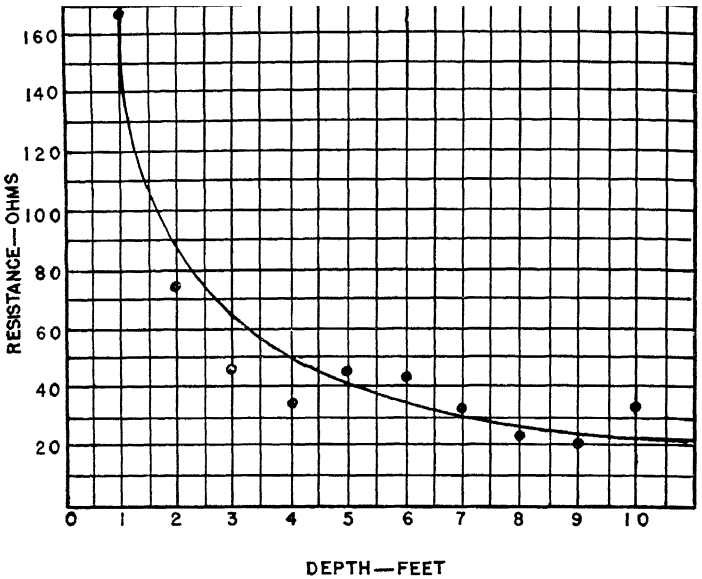

FIGURE 82.—*Effect of the length of a driven-pipe ground on its resistance to earth.*

be more economical to use two small plates in parallel and some distance apart. Likewise, a number of small widely separated rods or strips in parallel have a lower resistance to earth than a continuous piece having the same area.

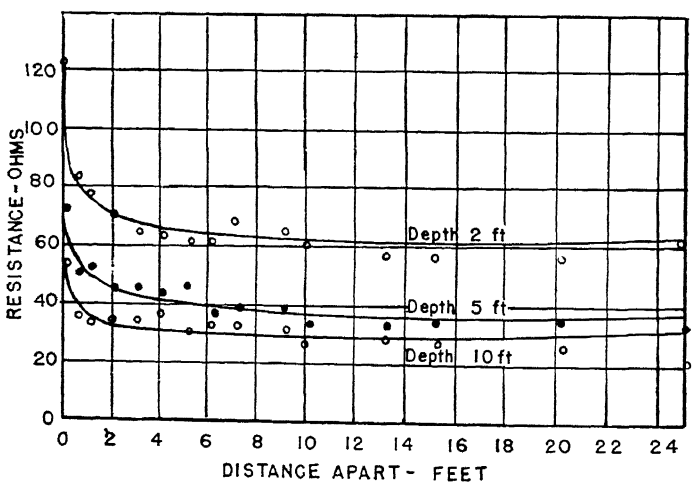

FIGURE 83.—*Effect of the distance apart of two driven-pipe grounds in parallel on their resistance to earth.*

(b) MATERIALS. A. IRON.—Because of its low first cost, low over-voltage and the low resistance of the corrosion products, junk iron, usually old pipe, is often used for anodes. When this is done, care should be taken to separate the individual pieces as much as possible and so to interconnect them that a break in the continuity of the group will not make

part of the electrodes useless. More than one connection to each piece should be made.

The kind of iron or steel used is unimportant. Boilers and parts of old engines and large machines have been used and also old well casings in place. If the current density at the surface of the iron is kept low, the anode will lose about 20 pounds per ampere-year plus some loss caused by local galvanic action. The latter will depend on the corrosivity of the soil and the homogeneity of the metal. If the current density is high, the rate of loss of metal may be less, since part of the current may cause the evolution of oxygen by the electrolysis of water in the soil. Additional energy will be required to ionize the water and still more to overcome

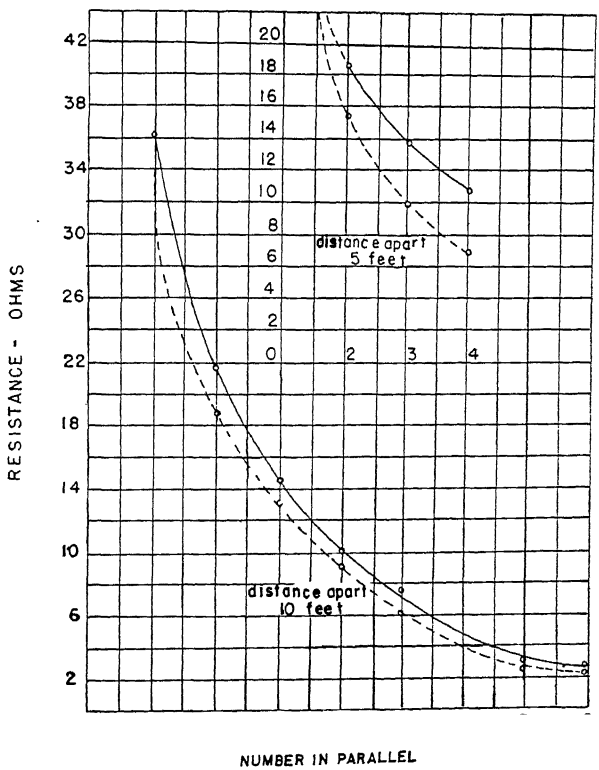

FIGURE 84.—*Effect of the number of 10-foot driven-pipe grounds in parallel on their resistance to earth.*

——— ∪ ——— = Observed values.
— — — O — — — = Calculated values.

the resistance resulting from the heating and drying of the soil. Usually, the cost of the electric energy will exceed the cost of the metal saved and on this account it is generally advisable to keep the current density low.

The relation of current density to corrosion efficiency has been investigated by McCollum and Logan [190], who found that the ratio of the actual to the theoretical loss of anode material ranged from 1.40 for a current density of 0.1 square centimeter to about 0.4 for a current density 20 times as great. They found also, that the addition of acids, alkali, and salts to the soils, materials which affect the self-corrosion of

iron, had little effect on the efficiency of electroyltic corrosion. An exception to this is the effect of the addition of chromates. This greatly reduces the efficiency of electrolytic corrosion, probably because the iron becomes passive. They found no definite relation between the electrolytic corrosion efficiency and the rate of self-corrosion. This indicates that the factors affecting the Corfield [54] corrosivity test are chiefly soil resistivity and polarization. The low corrosion efficiency when chromates are present suggests a means for making a substantially noncorrodible anode.

B. CARBON AND GRAPHITE.—When iron is not available, carbon or graphite rods are frequently used. Rhodes [159] and Roddey and Shepard [191] at one time used arc-furnace electrodes 2 inches in diameter and 6½ feet long. They were placed in holes 6 inches in diameter and 10 feet deep and surrounded by crushed coke or coke breeze. The resistance of these grounds ranged between 1 and 4 ohms.

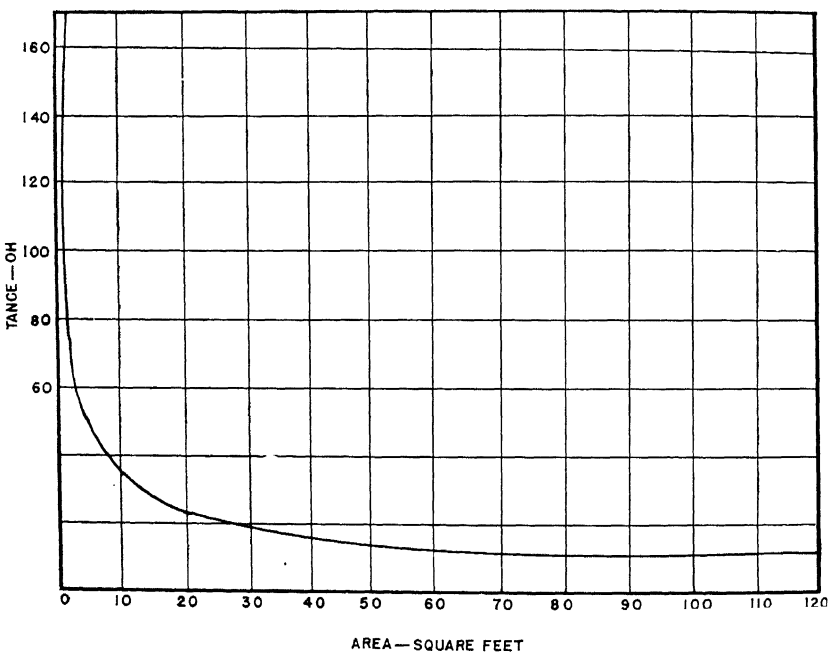

FIGURE 85.—*Effect of the diameter of a buried circular plate on its resistance to ground.*

To the IR drop caused by this resistance must be added a counter voltage of about 0.8 to 1.6 volts because of the potential of carbon with respect to steel.

According to Roddey and Shepard [191], the conduction between the carbon rod and the crushed coke is metallic and the rod does not deteriorate. There is a loss of the coke. A test which they ran indicated a loss of 0.000164 gram of coke per coulomb or 11.4 pounds per ampere-year. They attribute this loss partly to the formation of carbon dioxide, but mostly to the migration of the coke into the soil. The rate of loss of carbon anodes given above is greatly in excess of the value of 1.5 pounds per ampere-year given by Dorcas [192]. The latter is a

theoretical value based on the assumption that the loss of carbon is due entirely to the formation of carbon dioxide.

C. NONCORRODIBLE MATERIALS.—The cost of anode materials and their replacement has led to several suggestions for noncorroding anodes [193].

The user must decide whether it is cheaper to pay for material that must be replaced or for power required to generate and discharge oxygen from a noncorrodible anode. In certain cases an insoluble anode may be desired in order to avoid contamination of the electrolyte by corrosion products. Stainless steel and high-silicon cast iron have been suggested for this purpose, but few data applicable to cathodic protection are available.

(b) CATHODIC PROTECTION OF CITY NETWORKS

Most cathodic protection has been applied to cross-country lines under conditions that make interference with other lines improbable or easy to prevent. When one pipe system in the same street with other underground pipe or cable system is protected by causing current to flow to it, this current may flow onto and off the adjacent structures and damage them. The adjacent structures may also interfere with the desired distribution of current. It is necessary, therefore, to take special precautions if cathodic protection is applied to city networks.

Interference has been discussed by Smith [194]. The application of cathodic protection to city networks has been described by Kuhn [195], Schneider [196], and Wainwright [197]. It is advisable that all pipe owners in the neighborhood of a proposed cathodic protection be informed of its installation and be given an opportunity to participate in the work or at least to determine whether or not it affects their properties. A tentative plan for such cooperation has been proposed [198].

Two solutions to the problem of cathodic protection in cities may be considered. Often the preferable one is the protection of all structures in a neighborhood by the joint action of all interested parties. This involves an agreement as to the distribution of costs and adjustment of potentials, which is occasionally difficult to determine satisfactorily. The alternative is the application of protection to a single structure. If this is done, a current and potential survey or an exposure survey of all structures that may be affected should be made both before and after cathodic protection is applied. Anode locations and bonds or insulating joints should be adjusted until no structure is endangered. In some cases the least interference will be caused by a system of distributed anodes placed close to the pipe to be protected. This system has been patented by Rhodes [199], who permits its use without royalties under very reasonable conditions. However, arrangements for its use should be made in advance.

(c) CATHODIC PROTECTION OF TANK BOTTOMS

The protection of the bottoms of oil- and gas-storage tanks and the attached pipe systems is not different in principle from the protection of pipe lines. The same criteria for protection are used. Rectifiers are the most common source of power.

The protection of tanks has been described in some detail by Holsteyn [162], Brannon [163], and Bond [200]. The designs of the protection were based largely on the results of preliminary experiments sup-

plemented by experience in protecting pipe lines. Any one having a similar problem will receive considerable help from a careful reading of these papers.

(d) COST OF CATHODIC PROTECTION

The cost of cathodic protection will, of course, vary greatly with local conditions. A first approximation of the costs may be based on the experiences of others, but the cost of any installation and the effectiveness of the protection will depend to a large extent on the skill, experience, and foresight of the engineer in charge of the installation. For this reason, it is frequently economical to employ a consulting engineer to design and install the first system.

Wainwright [197] estimates the installation costs for an isolated anode system for a city distribution network as $700 to $1200 and the annual charges as 29 percent of the installation cost. For an installation of zinc anodes in Colorado, estimated to have a life of 20 years, Rhodes [199] reported a cost, including development charges, of $340 per mile plus $2.62 per anode. He used from 240 anodes per mile for a 4-inch pipe to 680 anodes per mile for 12-inch pipe. Wahlquist's [186] examinations indicated that in some soils 20 years is too long an estimate for the life of anodes of the size Rhodes used. The amount of power required for protection has already been discussed. The amount depends on the condition of the coating, the criterion for protection, and the position of the anode with respect to the pipe.

Roddey and Shepard [201] reported current requirements of 13.1 amperes per mile of 22-inch enamel-coated pipe and 8.3 amperes per mile of 14-inch felt-shielded asphalt-coated pipe. They report an average earth-to-pipe potential of about 0.3 volt; position and kind of reference electrode were not stated. Olson [178] reported that it required from 4.25 milliamperes per square foot to 1.5 milliamperes per square foot to protect bare gas lines in Louisiana and Texas. His criterion for protection was not stated, but his published curves indicate that he endeavored to make his pipe negative to a copper sulfate electrode by at least 0.85 volt.

Schneider [202] has prepared a digest of cathodic protection equipment costs. The economics of cathodic protections have been discussed by Thayer [203], who describes several sources of power and concludes that for every dollar spent for protection his company has saved from eight to ten dollars in replacements.

For the protection of a bare 10-inch line, Stewart [204] reports the use of thirty-four 8-volt 24 ampere rectifiers spaced a third of a mile apart. The annual cost of power was $0.013 per foot per year. On another bare line that was maintained 1-volt negative to a copper sulfate electrode, the current density ranged between 1.5 and 5 milliamperes per square foot. There were no leaks. Stewart's practice is to create a pipe-soil potential of at least 0.3 volt in excess of the potential existing before protection was installed.

Secrest [205] reports the 5-year average maintenance cost for twenty-eight 25-ampere windmills on 50-foot towers was $6.08 per year per mill. His distances between mills ranged from 1½ miles for bare pipe to 21 miles on asbestos-wrapped grease-coated pipe. A 4-month continuous record showed practically no protection 35 percent of the time. Coupons attached to the pipe show no corrosion.

(e) STATUS OF CATHODIC PROTECTION ENGINEERING

In the light of the foregoing, it is easy to see that at present the practice of applying cathodic protection is based largely upon judgment rather than upon definitely established engineering principles. The application of principles established by laboratory experiment is very difficult because the conditions encountered in practice are complex and difficult to determine. For example, the laboratorian has definite control of the composition, concentration, and homogeneity of the solutions he uses, and can easily arrange his experiments so that the electrodes employed have equipotential surfaces. Also, the supply of oxygen and the circulation of the electrolyte are under control. No such propitious state of affairs exists in nature. The corrosion engineer has to contend with variations in composition, concentration, and aeration, and in addition with limited accessibility for the measurement of currents and potentials. He also has to take into consideration certain time effects. When an electromotive force is applied between a pipe and an anode, the potential of the pipe changes gradually for hours or days and when the current is cut off the pipe is not immediately restored to its original potential. Furthermore, the relatively large currents and low resistances encountered in field work and the impossibility of isolating the soil and pipe with which the test is concerned from the adjacent soil and pipe make precise measurements in the field both difficult and time consuming.

The immediate problem of the cathodic protection engineer has been to effect a substantial reduction in losses due to corrosion in the shortest possible time, and there has been little time or equipment available for fundamental research. It is not surprising, therefore, that the criteria for judging whether or not complete protection has been achieved are not yet well established or that many reports are somewhat indefinite as to methods and results. It is generally agreed, however, that cathodic protection is an effective method of reducing corrosion and worthy of continued development. There is still much to be learned of the underlying phenomena involved in the corrosion of buried metal and of the practical conditions to be met in the field. From the nature of the problem, it is evident that the combined efforts of research workers and engineers will be required to bring about a satisfactory solution. No doubt, the problem will be attacked more intensively than is now possible as soon as the war is over.

XV. REFERENCES

[1] Second report of the Dutch Corrosion Committee II for the study of the corrosive effects of soils on pipes: Action of soil on pipes (1935).

[2] Report by the Dutch Corrosion Committee II for the study of the corrosive effects of soils on pipes: Coating of pipe with bituminous compositions (undated).

[3] Third report of the Dutch Corrosion Committee II for the study of the corrosive effect of soils on pipes: Regulations for the asphalting of pipes with asphaltic bitumen of the blown type (1937).

[4] C. A. H. von Wolzogen Kuhr and L. S. van der Vlugt, The gratification of cast iron as an electrobiological process in anaerobic soils, Water (Dutch) **18**, 147 (1934).

[5] H. Van der Veen, The investigation of the covering property of asphaltic coatings, Fourth NBS Underground Corrosion Conference (1937).

[6] C. M. Wichers, Corrosie van gegoten ijzeren buizen in den grond, Groningen, Rapport I (1932); II (1932); III (1935); IV (1937).

[7] C. M. Wichers, The corrosion of pipe lines due to earth contact, Fourth NBS Underground Corrosion Conference (1937).

[8] G. O. Thomas, Fundamental requirements of pipe coatings, Commonwealth Eng. 24, 293 (Australia, 1937).

[9] R. W. Parkhurst, Bituminous protective coatings for steel pipe, Commonwealth Eng. 24, 125 and 156 (Australia, 1936).

[10] G. O. Thomas, Determination of the suitability of bituminous coatings for underground use, Inst. Engrs. 6, 337 (Australia, 1934).

[11] C. C. Challis, Mitigation of corrosion on the distribution system of the Australian Gas Light Co., Fourth NBS Underground Corrosion Conference (1937).

[12] G. O. Thomas, The measurement of water absorption as a criterion of the protective properties of protective coating materials, Fourth NBS Underground Corrosion Conference (1937).

[13] C. M. Longfield, Stray current electrolysis in Australia, Fourth NBS Underground Corrosion Conference (1937).

[14] R. J. Dumas, Description of outer pipe coating, Fifth NBS Underground Corrosion Conference (1943).

[15] G. O. Thomas, Manufacture of coal tar enamel pipe coatings, Fifth NBS Underground Corrosion Conference (1943).

[16] J. C. Hudson, T. A. Banfield, and H. A. Holden, Tests on the corrosion of buried ferrous metals, Iron & Steel Inst. Paper No. 6 (England, 1942).

[17] H. J. Bunker, Micro-biological experiments in anaerobic corrosion, J. Soc. Chem. Ind. 58, 93 (England, 1939).

[18] W. G. Radley, Determination of the causes of sheath corrosion, Elec. Engrs. 57, 168 (1938).

[19] Report of the American Committee on Electrolysis, Am. Inst. Elec. Engrs. (New York, N. Y., 1921).

[20] U. R. Evans, Metallic corrosion, passivity and protection (Edward Arnold & Co., London, 1937).

[21] O. Krohnke, E. Maas, and W. Beck, Die Korrosion, Band 1 (Verlag von S. Hirzel, Leipzig, 1929).

[22] J. W. Shipley, The corrosion of cast iron and lead pipes in alkaline soil, J. Soc. Chem. Ind. 41, 311 (1922).

[23] J. W. Shipley and I. R. McHaffie, The graphite softening of cast iron, Ind. & Chem. Eng. 16, 573 (1924).

[24] J. W. Shipley, I. R. McHaffie, and N. D. Clare, Corrosion of iron in the absence of oxygen, Ind. & Chem. Eng. 17, 381 (1925).

[25] J. W. Shipley and I. R. McHaffie, The relation of hydrogen ion concentration to the corrosion of iron, Chem. & Met. 8, 121 (Canada, 1924).

[26] W. Nelson Smith, The principles of three-wire distribution for electric railways, Eng. J. 6 (No. 5) 235 (1923).

[27] E. P. Fetherstonhaugh, Studies of cast iron pipe corrosion, Fourth NBS Underground Corrosion Conference (1937).

[28] F. N. Speller, Corrosion, causes and prevention (McGraw-Hill Book Co., New York, N. Y., 1935).

[29] S. P. Ewing, Soil corrosion and pipe line protection, Am. Gas Assn. (New York, N. Y., 1938).

[30] R. M. Burns and A. E. Schuh, Protective coatings for metals (Reinhold Publishing Corporation, New York, N. Y., 1938).

[31] T. P. Hoar, The principles of metallic corrosion, Science of petroleum, p. 2307 (Oxford University Press, England, 1938).

[32] O. Gatty and E. C. R. Spooner, The electrode potential behavior of corroding metals in aqueous solutions (The Clarendon Press, Oxford, 1938).

[33] C. F. Marbut, Atlas of American agriculture, part III, Soils of the United States (U. S. Government Printing Office, 1935).

[34] Mark Baldwin, Chas. E. Kellogg, and James Thorp, Soil classification; Soils & Men, p. 979 (U. S. Government Printing Office, 1938).

[35] Kirk H. Logan, Engineering significance of National Bureau of Standards soil corrosion data, J. Research NBS 22, 109 (1939) RP1171.

[36] J. R. Baylis, Prevention of corrosion and red water, J. Am. Water Works Assn. 15, 596 (1926).

[37] W. G. Whitman, R. P. Russell, and V. J. Altieri, Effect of hydrogen-ion concentration on submerged corrosion of steel, Ind. Eng. Chem. 16, 665 (1924).

[38] W. G. Whitman and R. P. Russell, The submerged corrosion of iron, Soc. Chem. Ind. 43, 193T (1924).

[39] I. A. Denison and R. B. Hobbs, Corrosion of ferrous metals in acid soils, J. Research NBS 13, 125 (1934) RP696.

[40] I. A. Denison and S. P. Ewing, Corrosiveness of certain Ohio soils, Soil Sci. 40, 287 (1935).

[41] G. N. Scott, The use and behavior of protective coatings on underground pipes, Proc. Am. Petroleum Inst. [I] 10, 78 (1929).

[42] B. A. Keen, The Physical Properties of the Soils (Longmans Green & Co., New York, N. Y., 1931).

[43] T. D. Rice and L. T. Alexander, The physical nature of the soil, Soils & Men, p. 887 (U. S. Government Printing Office, 1938).

[44] H. G. Byers, M. S. Anderson, and Richard Bradfield, General chemistry of soils, Soils & Men, p. 911 (U. S. Government Printing Office, 1938).

[45] K. H. Logan, Soil-corrosion studies, 1934. Rates of loss of weight and pitting of ferrous specimens, J. Research NBS 16, 431 (1936) RP883.

[46] Soil Survey of Baltimore County, Md. (U. S. Government Printing Office, 1919).

[47] Melvin Romanoff, Effect of aeration on the hydrogen-ion concentration of soils in relation to the identification of corrosive soils, J. Research NBS 34, 227 (1945) RP1630.

[48] K. H. Logan, Soil-corrosion studies, 1937. Corrosion-resistant materials and special tests, J. Research NBS 23, 515 (1939) RP1250.

[49] E. R. Shepard, Some factors involved in soil corrosion, Ind. Eng. Chem. 26, 723 (1934).

[50] G. N. Scott, Adjustment of soil corrosion pit depth measurements for size of sample, Proc. Am. Petroleum Inst. [IV] 14, 204 (1934).

[51] E. P. Fetherstonhaugh, Discussion of underground corrosion, Proc. Am. Soc. Civil Engrs. 101, 828 (1936).

[52] J. F. Putnam, Soil corrosion, Proc. Am. Petroleum Inst. [IV] 16, 66 (1935).

[53] J. F. Brennan, A mathematical theory of corrosion, Gas Age-Record 75, 359 (1935).

[54] G. Corfield, Running a soil survey on a large distribution system, Western Gas, 6 (No. 3) 25 (1930).

[55] G. N. Scott, A preliminary study of the rate of pitting of iron pipe in soils, Proc. Am. Petroleum Inst. [IV] 14, 212 (1934).

[56] K. H. Logan, S. P. Ewing, and I. A. Denison, Soil corrosion testing, Symposium on Corrosion Testing Procedures, Am. Soc. Testing Materials, p. 95 (1937).

[57] K. H. Logan and M. Romanoff, Soil-corrosion studies, 1941: Ferrous and nonferrous corrosion-resistant materials and nonbituminous coatings, J. Research NBS 33, 145 (1944) RP1602.

[58] Report on steel pipe lines for underground water service, Underwriters Laboratories, Special Investigation 888, Appendix IV (1936).

[59] Standard for steel pipe lines for underground water service, Underwriters Laboratories, Special Investigation 888—38 (1938).

[60] K. H. Logan, W. Rogers, and J. F. Putnam, Pipe line currents, Am. Petroleum Inst. Production Bul. 204, 116 (1930).

[61] K. H. Logan, API pipe-coating tests—Final report, Proc. Am. Petroleum Inst. [IV] 21, 32 (1940).

[62] K. H. Logan, Soil corrosion studies, 1934. Rates of loss of weight and penetration of nonferrous materials, J. Research NBS 17, 781 (1936) RP945.

[63] R. J. McKay and R. Worthington, Corrosion resistance of metals & alloys (Reinhold Publishing Corporation, New York, N. Y., 1936).

[34] K. H. Logan, Soil corrosion studies 1939. Ferrous and nonferrous corrosion-resistant materials, J. Research NBS 28, 379 (1942) RP1446.

[65] W. W. H. Gee, Electrolytic methods for preventing corrosion, Trans. Faraday Soc. 9, 115 (1916).

[66] K. H. Logan and S. P. Ewing, Soil corrosion studies 1934. Field tests of nonbituminous coatings for underground use, J. Research NBS 18, 361 (1937) RP982.

[67] H. S. Rawdon, Protective metallic coatings (The Chemical Catalog Co., New York, N. Y., 1938).

[68] R. V. A. Mills, Protection of oil and gas fuel equipment against corrosion, U. S. Bureau of Mines Bul., 233 (1925).

[69] K. H. Logan, S. P. Ewing, and C. D. Yeomans, Bureau of Standards soil-corrosion studies I. Soils, materials and results of early observations, Tech. Pap. BS 22, 447 (1928) T368.

[70] C. O. Bannister, The protective action of zinc plates in boilers, Metal Ind. 41, 441-43, 467-70 (London, 1932).

[71] P. D. Merica, Structure of the coating on tinned sheet copper in a specific case of corrosion, Tech. Pap. BS 22 (1917) T90.

[72] B. M. McCollum and O. S. Peters, Surface insulation of pipes as a means of preventing electrolysis, Tech. Pap. BS 2 (1914) T15.

[73] G. N. Scott, API pipe coating tests: Progress reports I and II, Proc. Am. Petroleum Inst. [IV] 12, 55, 72 (1931); Progress report III, Proc. Am. Petroleum Inst. [IV] 13, 114 (1932); Progress report IV, Proc. Am. Petroleum Inst. [IV] 15, 18 (1934).

[74] E. R. Shepard, Measurement of the electrical conductance of nonmetallic coatings, Am. Gas J. 136, 22 (1932).

[75] S. P. Ewing, Field tests of protective coatings, Am. Gas Assn., Proc. p. 627 (1936).

[76] J. F. Putnam, Private communication.

[77] K. H. Logan, The effect of protective coatings on the rate of pitting of pipe lines, Proc. Am. Petroleum Inst. [IV] 22, 34 (1941).

[78] R. F. Hadley, Studies in microbiological anaerobic corrosion, Am. Gas Assn., Proc. p. 1764 (1940).

[79] T. D. Beckwith, The bacterial corrosion of iron and steel, Am. Water Works Assn. 33, 147 (1941).

[80] I. A. Denison, Electrolytic measurements of the corrosiveness of soils, J. Research NBS 17, 363 (1936) RP918.

[81] I. A. Denison, Making soil-corrosion survey by using electrolytic test, Oil & Gas J. 37 (No. 19) 96 (1938).

[82] A. Hickling, Studies in electrode polarization. Part I—The accurate measurement of the potential of a polarized electrode, Trans. Faraday Soc. 33, 1540 (1937).

[83] R. Darnielle, Measurement of electrode potentials and polarization in soil corrosion cells, J. Research NBS 25, 421 (1940) RP1336.

[84] L. C. Bannister and U. R. Evans, Passivity of metals, part V, the potential-time curves of some iron alloys, J. Chem. Soc. p. 1361 (1930).

[85] R. M. Burns, Corrosion of metals—I. Mechanism of corrosion processes, Bell System Tech. J. 15, 20 (1936).

[86] R. H. Brown and R. B. Mears, Application of electrochemical measurements to studies of the corrosion of 18-8 stainless steel, Trans. Faraday Soc. 35, 467 (1939).

[87] U. R. Evans, The distribution and velocity of the corrosion of metals, J. Franklin Inst. 208, 45 (1929).

[88] U. R. Evans and T. P. Hoar, The velocity of corrosion from the electrochemical standpoint, part II, Proc. Roy. Soc. [A] 137, 343 (1932).

[89] W. J. Müller, The effect of cathodic reaction on the corrosion of metals from the viewpoint of the local cell theory, Trans. Electrochem. Soc. 79, 169 (1939).

[90] O. Gatty and E. C. R. Spooner, The electrode potential behavior of corroding metals in aqueous solutions (Clarendon Press, Oxford, England, 1938).

[91] R. B. Mears, Discussion, Trans. Electrochem. Soc. 69, 164 (1936).

[92] U. R. Evans, L. C. Bannister, and S. C. Britton, Velocity of corrosion from the electrochemical standpoint, Proc. Roy. Soc. [A] 131, 367 (1931).

[93] Scott Ewing, Determination of the current required for cathodic protection, Am. Gas Assn. Proc. op. 613 (1940).

[94] I. A. Denison and R. B. Darnielle, Observations on the behavior of steel corroding under cathodic control in soils, Trans. Electrochem. Soc. 76, 199 (1939).

[95] I. A. Denison, Electrolytic behavior of ferrous and nonferrous metals in soil corrosion circuits, Trans. Electrochem. Soc. 81, 435 (1942).

[96] T. P. Hoar, The electrochemistry of protective metallic coatings, J. Electrodepositors' Tech. Soc. 14, 33 (1938).

[97] E. R. Shepard, Pipe line currents and soil resistivity as indications of local corrosive soil areas, BS J. Research 6, 683 (1931) RP298.

[98] F. Wenner, A method of measuring with resistivity, BS Sci. Pap. 12, 469 (1916) S258.

[99] W. J. Rooney, Earth resistivity measurements in the copper country, Michigan, Terrestrial Magnetism and Atmospheric Electricity 32, 97 (1927).

[100] Ground resistance testing, Tech. Bul. 1285 (James G. Biddle Co., Philadelphia, Pa., 1931).

[101] H. W. Wahlquist, Private communication.

[102] R. O. Davis, The use of the electrolytic bridge for determining soluble salts, U. S. Dept. Agr. Circular 423 (1927).

[103] Wm. E. Huddleston, The value of the radio balance in conducting soil surveys, Petroleum Ind. Elec. News 11 (No. 10) 53 (1942).

[104] B. B. Legg, Early steps in the development of a corrosivity apparatus, Natural Gas 12 (No. 2) 10 (1931).

[105] R. H. Hadley, Pipe coatings and corrosion research, Gas Age 92, 29 (Dec. 2, 1943).

[106] Burton McCollum and K. H. Logan, Earth resistivity and its relation to electrolysis of underground structures, National Bureau of Standards Tech. Pap. 23 (1916).

[107] H. D. Holler, Corrosiveness of soils with respect to iron and steel, Ind. Eng. Chem. 21, 750 (1929).

[108] I. A. Denison, Methods for determining the total acidity of soils, J. Research 10, 413 (1933) RP539.

[109] S. P. Ewing, Soil corrosion and pipe line protection (Am. Gas. Assn., 1938).

[110] J. F. Putnam, Electrolysis, Sibley J. Eng. 31, 88 (1917).

[111] K. H. Logan and E. A. Koenig, A comparison of methods for estimating the corrosivity of soils, Oil and Gas J. 38 (No. 27) 130 (1939).

[112] C. R. Weidner and L. E. Davis, Relation of pipe line currents and soil resistivity to corrosion, Proc. Am. Petroleum Inst. [IV] 12, 36 (1931).

[113] C. Fitzgerald, Discussion of relation of pipe line currents and soil resistivity to corrosion, by C. R. Weidner and L. E. Davis, Am. Petroleum Inst. [IV] 12, 47 (1931).

[114] Stanley Gill and Walter Rogers, Relation of long-line currents to corrosion, Physics 1, 194 (1931).

[115] Scott Ewing, Rough correlation between corrosiveness and resistivity for alkali soils, Oil and Gas J. 30, 29 (1932).

[116] K. H. Logan, W. F. Rogers, and J. F. Putnam, Pipe line currents, Oil and Gas J. 28 (No. 29) 130 (1930).

[117] J. C. Sterling, Pipe line currents, Oil and Gas J. 37 (No. 19) 142 (1938).

[118] C. H. McRaven, Measurements of pipe line currents, Petroleum Ind. Elec. News (April 1941).

[119] Carl Hering, Measurement of stray electric currents in underground pipes, Trans. Am. Inst. Elec. Engrs. 31, 1449 (1912).

[120] O. C. Mudd, Detecting pipe line corrosion with electrical devices, Oil and Gas J. 38 (No. 5) 48 (1939).

[121] O. C. Mudd, Use of soil surface potentials in locating pipe line corrosion, Oil and Gas J. 41 (No. 1) 50 (1942).

[122] C. M. Schlumberger and E. G. Leonardon, Location and study of pipe line corrosion by surface electrical measurements, Am. Inst. Mining Met. Engrs. Tech. Pub. No. 476 (1932).

[123] J. M. Pearson, Electrical instruments applied to the study of pipe line corrosion, Proc. Am. Petroleum Inst. [IV] 16, 75 (1935).

[124] B. McCollum and K. H. Logan, Electrolysis testing, Tech. Pap. BS (1927) T355.

[125] B. McCollum and K. H. Logan, Practical applications of the earth current meter, Tech. Pap. BS 21, 683 (1927) T351.

[126] W. R. Schneider, Corrosion coupons and pipe life predictions, Fifth NBS Underground Corrosion Conference (Abstract), Gas 20 (No. 4) 39 (1944).

[127] Valuation Docket 1203, Interstate Commerce Commission (1937).

[128] Stanley Gill, Locating pipe line inspection points, Oil Weekly (May 30, 1923).

[129] K. H. Logan and A. E. Koenig, Methods of inspecting pipe lines, J. Am. Water Works Assn. 31, 1451 (1939).

[130] D. F. Van deWater, Preventive maintenance by systematic pipe line inspection, Petroleum Eng. 14 (No. 8) 74 (1943).

[131] G. N. Scott, The use and behavior of protective coatings on underground pipes, Am. Petroleum Institute Bul. 10 (No. 2) 78 (1929); Oil and Gas J. 27 (No. 29) 127 (1929).

[132] S. P. Ewing and G. N. Scott, An electrolytic method for detecting the condition of a non-metallic pipe coating, Tenth annual Am. Gas Assn. Conference (1933).

[133] G. W. Clarvoe, The detection of flaws in pipe line protective coatings before burial, Pipe Line News 5 (No. 8) 13 (1933).

[134] D. Harrell, Detection of holidays in pitch enamel coatings, Petroleum Eng. 9, 97 (1936).

[135] D. E. Stearns, Accurate voltage control was a feature of new holiday detector, Petroleum Eng. 12, 160 (1941).

[136] D. E. Stearns, Electronic holiday detector provides robot pipe inspection service, Am. Gas Assn. Monthly 26 (No. 3) 115 (1944).

[137] J. M. Pearson, Electrical examination of coatings on buried pipe, Petroleum Eng. 12, 82 (1941).

[138] G. N. Scott and S. P. Ewing, Pipe line fabrics, Am. Dyestuff Reporter 24, 699 (1935).

[139] S. P. Ewing, Studies of coatings for pipe lines, Am. Gas Assn. Proc., p. 774 (1931).

[140] V. A. Grodsky, A laboratory soil corrosion test, Am. Water Works Assn. 30, 760 (1938).

[141] C. M. Wichers, The corrosion of pipe lines due to the earth contact, Fourth NBS Underground Corrosion Conference (1937). Unpublished.

[142] T. F. P. Kelly, Performance of coal tar protective coatings, Gas 20 (No. 6) 31 (1944).

[143] J. H. Peper, Use of cement in protecting underground pipe, Oil and Gas J. 32, (No. 33) 9; (No. 37) 34 (1934).

[144] L. E. Bredberg, Reconditioning lines in salt and marsh districts, Oil and Gas J. 33 (No. 3) 8 (1933).

[145] Standard specifications for coal tar enamel protective coatings for steel water pipe, Am. Water Works Assn. specification 7A. 5 (1940) 7A. 6 (1940).

[146] F. H. Love, Constructing the large diameter war emergency pipe line, Petroleum Eng. 14, 39 (1943).

[147] F. H. Love, Constructing the War Emergency Pipe products line, Petroleum Eng. 15, 133 (1944).

[148] J. C. Sterling, Field application of pipe line coatings, Fourth NBS Underground Corrosion Conference (1937). Unpublished.

[149] G. O. Thomas, Manufacture of coal tar enamel pipe coatings, Fifth NBS Underground Corrosion Conference (1943). Unpublished.

[150] W. F. Rogers, Performance data on enamel type pipe line coatings, Petroleum Eng. 14, 162 (1943).

[151] R. F. Hadley, Private communication.

[152] L. A. Hugo, Experience in the use of the Pearson Electronic Coating Inspector (Abstract), Oil and Gas J. 42 (No. 51) 50 (1944).

[153] G. B. McCabe and F. M. Hull, Detroit pioneers with pipe type gas filled cable, Elec. World 117 (No. 26) 2214 (1942).

[154] L. F. Sherer, Cooperative problems in cathodic protection, Oil and Gas J. 38 (No. 37) 179 (1939).

[155] G. I. Rhodes, Cathodic protection or electrical drainage of bare pipe lines (Monograph), Am. Gas Assn. (1935).

[156] W. Ryland Hill, Laboratory tests of cathodic protection of steel in various corrosive solutions, Petroleum Eng. 12 (No. 13) 51 (1941).

[157] W. F. Rogers, Relationship of current density to cathodic protection, Petroleum Eng. 12 (No. 1) 156 (1940).

[158] J. H. Keeling, Current and voltage needs for protecting steel submarine pipe lines, Gas 15 (No. 9) 31 (1939).

[159] G. I. Rhodes, Two unusual installations of cathodic protection, Proc. Am. Petroleum Inst. 17 (No. 4) 21 (1936).

[160] O. C. Mudd, Locating pipe line corrosion by soil surface potential measurements, Petroleum Ind. Elec. News 11 (No. 11) 17 (1942).

[161] R. J. Kuhn, Cathodic protection of underground pipe lines from underground corrosion, Proc. Am. Petroleum Inst. [IV] 14, 153 (1933).

[162] D. Holsteyn, Practical design and economics of a cathodic unit as applied in the refinery, Petroleum Ind. Elec. News 13 (No. 3) 9 (1943).

[163] R. A. Brannon, Cathodic protection of tank farms, Petroleum Ind. Elec. News 12 (No. 6) 11 (1942).

[164] S. P. Ewing, Cathodic protection of pipe lines from soil corrosion, Gas Age-Record 75 (No. 9) 179, (No. 10) 219, (No. 11) 239, (No. 12) 261 (1935); Natural Gas 16 (No. 3) 5, (No. 4) 16 (1935).

[165] R. J. Kuhn, Galvanic currents on cast iron pipe, First NBS Underground Corrosion Conference (1928). Unpublished. (Abstract) Ind. Eng. Chem. 22, 335 (1930).

[166] G. N. Scott, An analysis of certain circuits in cathodic protection, Proc. Am. Petroleum Inst. [IV] 23, 36 (1942).

[167] G. N. Scott, A rational approach to cathodic protection problems, Petroleum Eng. 12 (No. 8) 271 (1941).

[168] F. P. Bowden, The effects of pH on overpotential, Trans. Faraday Soc. 24, 473 (1928).

[169] J. M. Pearson, Null methods applied to corrosion measurements, Trans. Electrochem. Soc. 81, 485 (1942).

[170] K. H. Logan, Determination of current required for cathodic protection, Petroleum Eng. 14 (No. 10) 168 (1943).

[171] J. M. Pearson, Measurements of cathodic polarization and problems of interference on underground structures, Fifth NBS Underground Corrosion Conference (1943). Unpublished.

[172] G. R. Olson, Control of pipe line corrosion, Petroleum Eng. 14 (No. 12) 96 (1943).

[173] U. S. Patent 1962696 (1934).

[174] S. U. McGary, Determining the location and capacity of units for cathodic protection, Petroleum Eng. 9 (No. 11) 40 (1938).

[175] W. F. Rogers, Methods of designing cathodic protection installations, Petroleum Eng. 12 (No. 6) 100 (1941).

[176] Starr Thayer, The development and application of electrical protection for pipe lines, Proc. Am. Petroleum Inst. [IV] 14, 143 (1933).

[177] W. R. Schneider, Cathodic protection of pipe lines, Gas Age-Record 71 (No. 14) 355 (1933).

[178] G. R. Olson, Recent developments in cathodic protection of bare pipe lines, Petroleum Ind. Elect. News 12 (No. 7) 11 (1942).

[179] R. T. Fryer, Rectifiers, all types; comparison and operation, Petroleum Ind. Elect. News 14 (No. 1) 17 (1944).

[180] A. C. Aliter, The cathodic protection of bare steel pipe in western soil types by the use of zinc or aluminum, Convention Pacific Coast Gas Association (1941).

[181] G. R. Olson, A field experiment with magnesium rods, Proc. Nat. Assn. Corrosion Engrs. Convention 1, 56 (1944).

[182] J. J. Grebe and R. E. McNulty, Magnesium and anodes in cathodic protection, Fifth NBS Underground Corrosion Conference (1943).

[183] W. T. Smith and T. C. Marshall, Zinc for cathodic protection of pipe, Gas-Age 84 (No. 4) 15 (1939).

[184] C. L. Brockschmidt, A practical application of zinc anode protection to an 18 inch pipe line, Petroleum Ind. Elec. News 11 (No. 10) 31 (1941).

[185] O. C. Mudd, Experiences with Zinc Anodes, Petroleum Ind. Elec. News 13 (No. 1) 11 (1943).

[186] H. W. Wahlquist, Use of zinc for cathodic protection, Proc. Nat. Assn. of Corrosion Engrs. Convention 1, 61 (1944).

[187] W. R. Schneider, Pilot grounds for cathodic protection of pipe lines, Western Gas 10 (No. 8) 14 (1934).

[188] O. S. Peters, Ground connections for electrical systems, Tech. Pap. BS (1918) T108.

[189] O. H. Gish and W. J. Rooney, Measurement of resistivity of large masses of undisturbed earth, Terrestrial Magnetism and Atmospheric Electricity 30, 161 (1925).

[190] B. McCollum and K. H. Logan, Electrolytic corrosion of iron in soils, Tech. Pap. BS (1914) T25.

[191] O. C. Roddey and E. R. Shepard, Carbon anodes in an electrical drainage system, Fifth NBS Underground Corrosion Conference. Unpublished, (1943).

[192) M. J. Dorcas, Ground anodes, Fifth NBS Underground Corrosion Conference (1943).

[193] A. W. McAnney, Insoluble anodes, Petroleum Ind. Elec. News 10 (No. 3) (1940).

[194] A. V. Smith, Cathodic interference from cathodic protection installations, Am. Gas. Assn. Monthly 25, 421 (1943).

[195] R. J. Kuhn, Cathodic protection of pipe lines in city and country, Oil and Gas J. 36 (No. 18) 201 (1937).

[196] W. R. Schneider, Electrical protection of city networks, Fourth NBS Underground Corrosion Conference (1937).

[197] R. M. Wainright, Cathodic protection on distribution systems, Petroleum Ind. Elec. News 12 (No. 1) 33 1942.

[198] Intercompany procedure report, Petroleum Ind. Elec. News 12 (No. 2) 51 (1942).

[199] G. I. Rhodes, Electrical pipe line drainage with cost data, Elec. J. 33, 91 (1936).

[200] D. H. Bond, Cathodic protection of oil storage tank bottoms, Petroleum Eng. 11 (No. 6) 100 (1940).

[201] O. C. Roddey and E. R. Shepard, Distributed anode method cuts cost of cathodic protection, Oil and Gas J. 38 (No. 19) 84.

[202] W. R. Schneider, Comparing equipment costs in cathodic protection, a digest, Gas 15 (No. 6) 31 (June 1939).

[203] Starr Thayer, The application and economics of electrical protection of pipe lines, Proc. Am. Petroleum Inst. [IV] 17 (No. 12) 33 (1936).

[204] W. H. Stewart, Problems in connection with protection of bare pipe, Petroleum Ind. Elec. News 13 (No. 2) 17 (1943).

[205] L. C. Secrest, Cathodic protection—its application to a pipe line, Oil and Gas J. 43 (No. 3) 82 (1945).

[206] R. K. Schofield, The pF of water in soil, Trans. Third Intern. Cong. Soil Sci. 2, 37 (England, 1935).

XVI. APPENDIX 1. COOPERATORS WITH THE NATIONAL BUREAU OF STANDARDS IN THE CORROSION INVESTIGATIONS

1. FURNISHERS OF LABOR AND OF TEST SITES

Albuquerque Gas & Electric Co.
Alexandria Water Co.
City of Atlanta, Department of Water Works.
Atlanta Gas Light Co.
Atlantic City Gas Co.
Atlantic Pipe Line Co.
City of Baltimore, Department of Public Works.
Boston Consolidated Gas Co.
Brockton Gas Light Co.
Camden Water Department.
Carolina Power & Light Co.
Cincinnati Gas & Electric Co.
City of Charleston, Water Department.
The Citadel.
City of Cleveland, Department of Public Utilities.
Colorado Interstate Gas Co.
Community Natural Gas Co.
Dallas Gas Co.
Delaware Power & Light Co.
Des Moines Gas Co.
Duke Power Co.
East Bay Municipal Utility District.
East Ohio Gas Co.
Empire Pipe Line Co.
Equitable Gas Co.
Florida Power & Light Co.
Florida Public Utilities Co.
Georgia Railway & Power Co.
Gulf Oil Corporation.
Humble Pipe Line Co.
Indiana Pipe Line Co.
City Commission of Jacksonville.
Jacksonville Gas Co.
City of Kalamazoo, Dept. of Public Utilities.
Kansas City Gas Co.
Los Angeles Gas & Electric Co.
Macon Gas Co.
Memphis Board of Water Commissioners.
City of Meridian.
City of Middleboro, Mass.
Midwest Refining Co.
City of Milwaukee, Dept. of Public Works.
Milwaukee Gas Light Co.
Mississippi Power Co.
Mississippi River Fuel Corporation.
City of Mobile, Water Works Department.
Mountain Fuel Supply Co.
New Orleans Audubon Park Commission.
New Orleans Sewerage & Water Board.
New Orleans Public Service, Incorporated.
North Carolina Public Service Co.
Northern States Power Co.
City of Norwood, Mass.
Ohio Fuel Gas Co.
Oklahoma Pipe Line Co.
The Omaha and Council Bluffs Electrolysis Committee.
Pacific Gas & Electric Co.
Pensacola-Gulf Power Co.
People's Water & Gas Co.
Philadelphia Electric Co.
City of Phoenix, Water Department.
Prairie Pipe Line Co.
Public Service Company of Colorado.
Pueblo Gas & Fuel Co.
Pure Oil Pipe Line Co.
Raleigh Gas Co.
City of Rochester, Dept. of Public Works.
Rochester Gas & Electric Company.
San Antonio Public Service Board.
San Diego Consolidated Gas & Electric Co.
San Joaquin Light & Power Corporation.
City of Seattle, Department of Public Works.
Shell Oil Co.
Shell Petroleum Corporation.
Shell Pipe Line Corporation.
Sinclair Pipe Line Co.
Sinclair-Prairie Pipe Line Company of Texas.
Sohio Pipe Line Co.
Southern California Gas Co.
Southern California Telephone Co.
Southern Cities District Co.
Southern Natural Gas Co.
Southwestern Gas & Electric Co.
City of Springfield, Ohio, Water Department.
Springfield Railway Co.
Standard Oil Company of California.
Standard Oil Company of Louisiana, Pipe Line Dept.
Standard Oil Development Co.
Standard Oil Company of New Jersey.
Stanolind Oil & Gas Co.
Sun Oil Line Co.
Susquehanna Pipe Line Co.
Tampa Gas Co.
Tidal Pipe Line Co.
Tidewater Pipe Line Co., Ltd.
Tri City Railway & Light Co.
United Gas Pipe Line Co.
The United Light & Power Service.
Union, Light, Heat & Power Co.
Union Light & Railway Co.
Union Oil Company of California.
Vicksburg Gas Co.
Wilmington Gas Co.

2. SUPPLIERS OF MATERIALS

(a) FERROUS

Allegheny Ludlum Steel Corporation.
American Cast Iron Pipe Co.
American Radiator Co.
American Rolling Mill Co.
H. A. Brassert Co.
A. M. Byers Co.
Carnegie-Illinois Steel Corporation.
Carson Cadillac Corporation.
The Duriron Co., Inc.
Electric Steel Founders.
Electro Metallurgical Co.
Inland Steel Co.
The International Nickel Co., Inc.
Jones and Laughlin Steel Corporation.
Lukenheimer Co.
McWane Cast Iron Pipe Co.
Meehanite Metals Co.
National Cast Iron Pipe Co.
National Tube Co.
Nugent Steel Casting Co.
Pittsburgh Valve, Foundry & Construction Co.
Reading Iron Co.
Republic Steel Corporation.
Sharon Steel Corporation.
Sivier Steel Castings Co.
Stockham Pipe & Fittings Co.
Union Carbide & Carbon Research Laboratories.
United States Pipe & Foundry Co.
Walworth Co.
Youngstown Sheet & Tube Co.

(b) NONFERROUS

American Brass Co.
American Smelting & Refining Co.
American Zinc Products Co.
Bell Telephone Laboratories Inc.
Bridgeport Brass Co.
Brown Co.
Chase Brass & Copper Co.
General Cable Corporation.
Habirshaw Electric Cable Co.
The Hoyt Metal Co.
Y. T. Hungerford Brass & Copper Co.
Illinois Zinc Co.
Johns-Manville Sales Corporation.
Keasby & Mattison Co.
Lumen Bearing Co.
Mueller Brass Co.
Mueller Co.
National Carbon Co.
National Lead Co.
The New Jersey Zinc Co.
Revere Copper & Brass, Incorporated.
Scovill Manufacturing Co
Sharon Steel Hoop Co.
Standard Underground Cable Co.

(c) COATINGS

Albrecht Pagenstecher.
Aluminum Company of America.
American Machine & Foundry Co.
American Tar Products Co.
Arco Co.
The Bakelite Co.
Ball Chemical Co.
Barber Asphalt Co.
The Barrett Co.
Benjamin Foster Co.
Calorizing Co.
Chadeloid Chemical Co.
Consolidated Gas Company of New York.
Dearborn Chemical Co.
E. I. du Pont de Nemours & Co., Inc.
Eagle-Picher Lead Co.
Emulsion Process Co.
Ferro Enamel Corporation.
Fish-Schurman Corporation.
The Flintkote Co.
General Paint Corporation.
The P. D. George Co.
The B. F. Goodrich Rubber Co.
Goodyear Tire & Rubber Co.
Harpoon Paint Products, Incorporated.
Headley Emulsified Products Co.
Hill, Hubbell, & Company.
Inertol Co.
Iroquois Gas Corporation.
Irvington Varnish & Insulator Co.
The Locomotive Terminal Improvement Co.
McEverlast, Inc.
Andrew McLean Co.
Merchants Basket & Box Co.
Paraffine Companies, Inc.
Pioneer Asphalt Co.
Resisteor Engineering Corporation.
H. H. Robertson Co.
Shori Process Corporation.
Sherwin-Williams Co.
Jas. B. Sipe & Co.
Southport Paint Co., Inc.
Technical Products, Inc.
The Texas Co.
Thiokol Corporation.
Udylite Process Co.
United Gas Impressment Co.
Wailes Dove—Hermiston Corporation.

3. ADVISORY ORGANIZATIONS

American Committee on Electrolysis, Research Subcommittee.
American Engineering Standards Committee.
American Foundrymen's Association.
American Gas Association.
American Petroleum Institute.
American Society for Testing Materials.
American Standards Association.
American Water Works Association.
American Zinc Institute, Inc.
Asphalt Institute.
Cast Iron Pipe Research Association.
Copper and Brass Research Association.
Lead Industries Association.

4. GOVERNMENT DEPARTMENTS

Department of Agriculture, Bureau of Plant Industry.
Department of Commerce, National Bureau of Standards.
Department of Interior: Bureau of Mines, Geological Survey (Water Resources Branch).

XVII. APPENDIX 2. DESCRIPTIONS OF SOILS AT TEST SITES

TABLE 101.—*National Bureau of Standards test sites.*

Prepared by M. Romanoff. The profiles have been described by S. Ewing, I. A. Denison, G. N. Scott, and by the following soil surveyors from the Bureau of Plant Industry of the United States Department of Agriculture: A. E. Taylor, M. H. Lapham, R. Wildermuth, W. J. Geib, H. H. Bennett, H. G. Lewis, F. A. Hayes, W. T. Carter, R. C. Roberts, Mark M. Baldwin, R. S. Smith.

When the profile at the test site was not described the typical profile of the soil type was taken from soil-survey reports.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
1	Allis silt loam	Cleveland, Ohio	0–8 grayish yellow or yellowish gray silt loam mottled with yellow and yellowish brown. 8–23 mottled yellow and gray silty clay loam which contains fragments of shale. 23–30 bluish gray silty clay loam with bands of yellow indicating the bedding planes of the shale. 31–70 silty clay or silty clay loam layer of shale which has a bluish gray color and is streaked along bedding planes with yellow. 70–96 reddish brown shale streaked with gray 76–90 compact bluish gray shale with yellowish brown and reddish brown streaks. 96–100 the streaks become less conspicuous This shale runs high in aluminum sulfate, which, with water, breaks down into aluminum hydroxide and sulfuric acid.	Poor	Undulating to gently rolling.	95
2	Bell clay	Dallas, Tex.	0–10 black to dark brown silty clay 10–740 black clay. No definitely residual matter was discovered within 40 inches. Small rounded quartzite gravel and lime concentrations disseminated through the subsoil.	do	Level	Below 40
3	Cecil clay loam	Atlanta, Ga.	0–8 grayish brown, rather compact, very fine sandy loam. A few fragments of granite and quartz found on the surface. 8–10 transition layer into 10–32 compact brittle red clay containing very few mica flakes and practically no sand and stones. 32–70 micaceous, more friable, and not as compact as above horizon, red clay loam or clay. 48–52 layer of sandy clay with yellowish mottlings 52–70 red micaceous clay as in 32–48 70–74 red very fine sandy loam with yellowish mottlings 74–96 moderately friable red very fine sandy loam, full of mica crystals, and having a few brownish and yellowish mottlings due to partially decomposed rock. 96–108 very friable fine sandy loam, mottled yellow, red, and brown.	Little excessive	Moderate slope.	30

Chester loam	Jenkintown, Pa.	0–10 grayish brown mellow loam gradually getting lighter in color with increasing depth. The top 6 inches of the trench is a mixture of road material and soil. No vegetation. 10–34 mellow, only slightly darker in color and heavier in texture with increasing depth. 34–96 micaceous rather loose friable silt loam containing considerable fine sand. At 36 inches there is a layer of partially decomposed granite. Soil in this site is considerably wetter than the average condition of this soil, as the trench gets all the rain water that falls on the adjacent highway.	Good	Gently rolling	36
Dublin clay adobe	Oakland, Calif.	0–10 dark dull gray or drab clay of adobe structure, sticky when wet, contains numerous plant and grass roots and an appreciable amount of fine gritty material and gravel fragments. 10–36 slightly more compact brownish gray or drab friable clay which is sticky when wet. Somewhat mottled with brown and dull slaty gray or black streaks. It contains spherical shotlike iron concretions of black or bluish black color, ranging in size from a pinhead to small buckshot. 36–48 soil grades into a yellowish brown silty clay material. This horizon is mildly calcarious and is the upper limit of lime accumulation. 48–60 yellowish brown compact clay containing many light grayish fragments of lime carbonate nodules localized in thin seams or layers, the material being partially cemented.	Poor	Smooth and level.	30
Everett gravelly sandy loam	Seattle, Wash.	0–8 brown to light brown sandy loam darkened by presence of organic matter. 8–24 light brown sandy loam. Both this and the above horizon contain little gravel, and considerable coarse sand. Both horizons are loose and friable and contain numerous grass roots. 24–30 grayish brown gravelly sandy loam. Slightly compact. Below 30 inches hard cemented gravel and sand, with very little lime of a grayish brown color.	Excessive	Moderately rolling.	36
Maddox silt loam	Cincinnati, Ohio	0–5 brownish yellow friable silty clay loam. 5–15 brownish yellow smooth, plastic, heavy, moderately tight clay mottled light gray. The mottles are of moderate extent and development and occur in small irregular veins. The soil material fractures into irregularly shaped lumps, ranging in size from ½ to 1½ inches in diameter. 15–22 brownish yellow or yellow sticky, plastic, slowly pervious, moderately compact heavier clay containing a moderate amount of light gray mottles. It has a fragmental structure forming hard, irregular aggregates from ½ to 1½ inches in diameter. 22–30 varicolored bluish gray and olive-green tight, smooth, plastic, very heavy clay or silty clay having occasional staining of rust-yellow. This layer has been developed from the weathering of underlying shale rock materials.	Fair	Smooth ridge top.	22

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
8	Fargo clay loam	Fargo, N. Dak.	0–24 black noncalcareous clay loam. Rather friable. Breaks with concoidal fracture into pea-size pieces. 24–42 calcareous transition layer with tongues of both horizons extending into the layer. 42–88 grayish brown heavy clay loam. Light gray when dry—highly calcareous. Below 88 parent material of old lake laid deposits. Grayish brown color containing rusty brown streaks and mottlings. Few hard concretions that are largely lime.	Poor	Level	66
9	Genesee silt loam	Sidney, Ohio	0–10 brownish gray silt loam, slightly streaked with reddish brown. 10–16 gray loam streaked reddish brown and mottled yellowish brown and brownish yellow. 16–22 transition to fine sandy loam mottled reddish brown. At 22 bed of gray gravel.	do		22
10	Gloucester sandy loam	Middleboro, Mass.	Surface—light brown sandy loam. Subsoil—light grayish brown fine sandy loam containing some gravel.	Fair		36
11	Hagerstown loam	Baltimore, Md.	0–12 dark brown or brown friable loam. 12–33 reddish brown or red clay loam. Moderately compact. Contains fragments of stone, chert. 33+moderately friable rusty brown heavy silt loam with a reddish cast. This extends to the underlying rock, which is rather clear, crystalline, and hard (not limestone). In one place in the trench the rock is at a depth of about 4 feet.	Good	Slight slope	36
12	Hanford fine sandy loam	Los Angeles, Calif.	The entire profile is a grayish brown friable, loose, micaceous fine sandy loam containing thin layers of material as heavy as loam and as tight as sand. Noncalcareous at surface, and only faintly calcareous at 6 feet. This soil differs from soil 13 in that it does not contain soluble carbonates in appreciable amount.	do	Practically level.	24
13a	Hanford very fine sandy loam	Bakersfield, Calif.	0–56 light grayish brown smooth, friable, micaceous very fine sandy loam. 56–62 light grayish brown very fine sand. 62–68 same as 0–56. 68–72 same as 56–62. The soil is high in alkali in the carbonate form, and formerly called black alkali.	Fair	Almost level	30

13b	....do.....	....do.....	0–6 grayish brown very slightly compacted loam..... 6–84 light grayish brown friable loose micaceous very fine sandy loam. Numerous roots in first 3 feet. Few light colored specks at 3 feet. A special set of specimens are buried at the site. The profile is similar to site 13a, but differs by being low in alkali content.	Good.....	Very gently undulating.	
14	Hempstead silt loam.....	St. Paul, Minn.....	0–15 dark brown (almost black) silt loam..... 15–24 transition layer consisting of tongues and streaks of the two adjoining horizons extending into each other. 24–42 brown silt loam with yellowish cast, slightly compact..... 42+ grayish brown sand containing some gravel..... Entire profile is noncalcareous.....	Fair.....	....do.....	44
15	Houston black clay.....	San Antonio, Tex.....	0–36 black clay with no appreciable change. Highly calcareous.. Small fragments of lime are found throughout the section.....	Poor.....	.....	36
16	Kalmia fine sandy loam.....	Mobile, Ala.....	0–8 grayish brown fine sandy loam, which appears to have been disturbed. 8–42 yellowish brown very fine sandy loam. Texture gradually gets finer and compactness increases with depth. Some reddish mottlings and a few iron concretions about ¼ inch in diameter, which are most numerous at about 3 feet and disappear at 6 feet. 42–48 brownish yellow or yellow silt loam mottled with red..... 48–96 mottled red, gray, and yellow material containing thin layers of clay and fine sand but with the average texture of silt loam. Below 72 inches the color is light yellowish brown with light gray mottlings.	Fair.....	Gentle slope...	30
17	Keyport loam.....	Alexandria, Va.....	0–6 grayish brown loam or silt loam without structure. Moderately loose and friable. 6–14 transition layer, slightly compact clay loam..... 14–48 light yellowish brown rather compact clay loam with concoidal fracture exposing shiny surfaces. Slightly mottled with gray. Texture gets a little lighter with increasing depth. 48–74 brown fine sandy loam with slight reddish cast..... 74–76 light gray clayey sand..... 76–96 brown sand almost saturated with water..... 96+ gravel..... Entire profile is noncalcareous.....	....do.....	....do.....	36
18	Knox silt loam.....	Omaha, Neb.....	0–8 dark brown silt loam full of brickbats, plaster, rotten wood, etc. The surface soil partly removed and mixed with foreign matter. 8–72 light brown very uniform smooth friable silt loam that gets a little lighter in color with depth. Moderately moist. Contains a few brown spots due to rotten roots at 8 to 24 inches. Very faintly calcareous at 48 inches and below.	Good.....	Practically level.	48

13b	....do.....	....do.....	0–6 grayish brown very slightly compacted loam..... 6–84 light grayish brown friable loose micaceous very fine sandy loam. Numerous roots in first 3 feet. Few light colored specks at 3 feet. A special set of specimens are buried at the site. The profile is similar to site 13a, but differs by being low in alkali content.	Good.....	Very gently undulating.	
14	Hempstead silt loam.....	St. Paul, Minn.....	0–15 dark brown (almost black) silt loam..... 15–24 transition layer consisting of tongues and streaks of the two adjoining horizons extending into each other. 24–42 brown silt loam with yellowish cast, slightly compact..... 42 + grayish brown sand containing some gravel..... Entire profile is noncalcareous.....	Fair.....	....do.....	44
15	Houston black clay.....	San Antonio, Tex.....	0–36 black clay with no appreciable change. Highly calcareous.. Small fragments of lime are found throughout the section.....	Poor.....	.....	36
16	Kalmia fine sandy loam.....	Mobile, Ala.....	0–8 grayish brown fine sandy loam, which appears to have been disturbed. 8–42 yellowish brown very fine sandy loam. Texture gradually gets finer and compactness increases with depth. Some reddish mottlings and a few iron concretions about ¼ inch in diameter, which are most numerous at about 3 feet and disappear at 6 feet. 42–48 brownish yellow or yellow silt loam mottled with red..... 48–96 mottled red, gray, and yellow material containing thin layers of clay and fine sand but with the average texture of silt loam. Below 72 inches the color is light yellowish brown with light gray mottlings.	Fair.....	Gentle slope...	30
17	Keyport loam.....	Alexandria, Va.....	0–6 grayish brown loam or silt loam without structure. Moderately loose and friable. 6–14 transition layer, slightly compact clay loam..... 14–48 light yellowish brown rather compact clay loam with concoidal fracture exposing shiny surfaces. Slightly mottled with gray. Texture gets a little lighter with increasing depth. 48–74 brown fine sandy loam with slight reddish cast..... 74–76 light gray clayey sand..... 76–96 brown sand almost saturated with water..... 96 + gravel..... Entire profile is noncalcareous.....	....do.....	....do.....	36
18	Knox silt loam.....	Omaha, Neb.....	0–8 dark brown silt loam full of brickbats, plaster, rotten wood, etc. The surface soil partly removed and mixed with foreign matter. 8–72 light brown very uniform smooth friable silt loam that gets a little lighter in color with depth. Moderately moist. Contains a few brown spots due to rotten roots at 8 to 24 inches. Very faintly calcareous at 48 inches and below.	Good.....	Practically level.	48

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
19	Lindley silt loam	Des Moines, Iowa	0–4 dark brown silt loam, friable and full of organic matter. 4–18 slightly compact heavy silt loam, yellowish brown. 18–34 transition layer into. 24–50 rather compact more yellowish brown clay containing a few dark-colored specks. 50–76 grayish brown clay loam with bright yellow mottlings and a few white specks. Less compact than above. 76–84 gritty material of variable texture and color, containing light colored cherty material. 84 large boulder or gravel.	Good	Moderate slope.	36
20	Mahoning silt loam	Cleveland, Ohio	0–4 brownish gray heavy silt loam or light silty clay loam. 4–8 pinkish red clay, mottled brownish yellow, yellow, yellowish brown, and gray. 8–24 mottled drabbish gray-yellow, brownish yellow, and yellowish brown clay. 24–46 drabbish gray clay, mottled with brownish yellow, and pinkish red. 46–50+ mottled gray, brownish yellow, and yellowish brown, calcareous clay.	Poor	Gently undulating.	48
21	Marshall silt loam	Kansas City, Mo.	0–28 brown or chocolate brown friable, uniform silt loam. 28–36 transition layer. 36–84 light brown silt loam very uniform and smooth. Noncalcareous to 6 feet. 84+ light brown noncalcareous clay slightly mottled with grayish brown.	Good	Moderately rolling.	60
22	Memphis silt loam	Memphis, Tenn.	0–4 light brown silt loam containing thin discontinuous layers of darker color probably due to the turning under of organic matter when the soil was cultivated. 4–96 light brown slightly compact silt loam with some grayish mottlings but no hard lime concretions. Very uniform in color and texture.	do	Very gently undulating.	33
23	Merced silt loam	Buttonwillow, Calif.	0–14 dark brown (almost black) silt loam. ¼-inch crust, 3-inch mulch, which is underlaid by slightly compact very lightly moist material with no definite structure. 14–72 light gray loam, moderately compact and moist with somewhat lighter texture and a more open structure below 48 inches, where thin layers of sandy loam occur. Friable and loose. Thin layers of grayish brown sand occur at 60 inches. Location has all indications of a soil high in alkali. Highly calcareous up to surface.	Poor	Level	30

24	Merrimac gravelly sandy loam.	Norwood, Mass.	0–4 brown loam containing considerable sand and coarse sand. 4–33+ grayish coarse sand or fine gravel.	Good		33
25	Miami clay loam	Milwaukee, Wis.	0–6 grayish brown silt loam. 6–30 yellowish brown, stiff, heavy clay loam to clay, containing a small amount of gritty material. 30–48 slightly calcareous brownish yellow heavy clay loam, somewhat lighter than the above and also contains some gritty material.	Fair		36
26	Miami silt loam (mottled phase).	Springfield, Ohio	0–2 grayish brown silt loam. 2–7 brownish gray to yellowish-gray silt loam. 7–10 gray silt loam mottled faintly with yellow. 10–16 mottled yellow and gray silt loam. 16–24 brown clay loam to clay mottled brownish yellow and yellowish brown. 24–36 reddish brown stiff clay. 36–48 yellowish brown gravelly friable clay, somehwat calcareous in the lower part of the layer.	Good		36–48
27	Miller clay	Bunkie, La.	Dull red heavy calcareous clay extending down below the depth at which the specimens are buried. Soil map shows Miller clay at this location and a sample of the soil was identified as typical Miller clay.	Very poor	Level	30
28	Montezuma clay adobe	San Diego, Calif.	0–8 filled material—brickbats, gravel, etc. 8–46 gray or light grayish-brown adobe containing some gritty material and gravel in the first foot. Noncalcareous. 46–50 light gray sandy clay, somewhat sticky. 50–60 grayish brown or yellowish brown gravelly sand. 60+ gravel.	Poor	Level to gently rolling.	40
29	Muck	New Orleans, La.	Surface—to varying depths consists of dark colored material of variable texture, most of which is fill. Subsoil—black, semifluid mass of well-decomposed mulch which rests upon an almost solid mat of old cypress stumps and roots that are in an excellent state of preservation. Substratum—stiff, putty-like gray clay. The land was originally a cypress swamp.	Very poor		24
30	Muscatine silt loam	Davenport, Iowa	0–6 dark brown silt loam (grayish brown when dry). 6–72 gray or grayish brown silt loam with yellow mottlings that are evenly distributed and containing a few brown specks. Noncalcareous throughout.	Poor	Level	36
31	Norfolk fine sand	Jacksonville, Fla.	0–4 grayish brown fine sand containing organic matter. 0–15 gradual transition into very slightly compact, very pale yellow sand. Deepest in color and more compact at 15 inches. 15+ compactness gradually decreases and the color gets a little lighter. Slight yellow mottlings at 60 inches. The same sand probably extends to 20 or 30 feet. This soil was called Norfolk sand in previous soil corrosion reports.	Good	Almost level	24

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
32	Ontario loam	Rochester, N. Y.	0–8 brown to grayish brown (when dry) mellow and friable, fine sandy loam to fine sand. 8–18 slightly more compact, though crumbly loam to fine sandy loam, light brown to yellowish brown in color. 18–33 grayish brown to brownish gray compact loam in place, though friable when bored out. 33 + partially weathered till material Parent material from which the soil is derived is largely limestone, with some sandstone, shale, and igneous rocks. Gravel and small stones are abundant in lower portions. The soil is calcareous at from 15 to 24 inches.	Good	Gently sloping to undulating.	48
33	Peat	Milwaukee, Wis.	A black well-decomposed peat 30 to 36 inches deep, where it rests on a drab or bluish plastic clay loam. The lower part of the section was saturated with water. The peat merges into clyde loam, the line of separation being rather indefinite. A sample of this soil lost 42 percent on ignition	Very poor		24
34	Penn silt loam	Norristown, Pa.	0–8 brown or dark brown silt loam 8–24 reddish brown silt loam containing considerable sand 24–38 slightly lighter in color than above layer 38–56 Indian red or reddish-brown silt loam 56 + shale	Good	Gentle slope	36
35	Ramona loam	Los Angeles, Calif.	0–22 light brown moderately compact loam with slight reddish tint and a slight admixture of organic matter to 2 inches of surface. Very dry. 22–54 slightly moist, hard, gritty, compact, brittle, reddish brown clay loam containing numerous white specks. 54–72 light reddish brown or light-brown gritty silt loam. White specks present but not as compact as horizon above. Entire profile is noncalcareous	Fair	Moderately rolling.	36
36	Ruston sandy loam	Meridian, Miss.	0–8 light brown, loose, friable sandy loam 8–30 brownish red or rusty brown heavy fine sandy loam. Rather compact and hard. 30–60 reddish brown, rather compact, heavy fine sandy loam 60–96 mottled red and yellow compact heavy fine sandy loam No gravel or stones present in the profile	Good	Gently rolling.	36

37	St. John's fine sand	Jacksonville, Fla.	0–2 dark gray or grayish brown fine sand. The organic matter imparts the dark color. 2–10 the material merges into a rather compact yellowish layer having a distinct lower boundary. The organic matter decreases with depth and the yellow color becomes brighter. The yellow sand contains a few very hard round black iron concretions about ¼ inch in diameter that are surrounded by reddish brown sand. 10–28 light gray slightly compact fine sand which becomes lighter with increasing depth and is almost white at 28 inches. 28–36 dark brown hard compact iron cemented hardpan with the characteristic coffee ground color. 36–60 pale yellow fine sand saturated with water	Poor	Practically level.	30
38	Sassafras gravelly sandy loam.	Camden, N. J.	0–8 grayish brown gravelly sandy loam which gradually changes into a light yellowish brown or yellowish gray. 8–28 light gray or yellowish brown gravelly sandy loam which is darker than the horizon below. 28–96 light gray gravelly sandy loam with faint yellow cast. Entire profile is loose and open and is noncalcareous. The amount of gravel is rather small for a gravelly type soil. The size of the gravel varies up to 8 inches in diameter and is all smooth and water-worn.	Good	Moderate uniform slope.	30
39	Sassafras silt loam	Wilmington, Del.	This soil has been so disturbed that an accurate description of the profile is impossible. 0–12 grayish brown moderately friable silt loam. 0–30 + slightly yellowish-brown silt loam which extends below the specimens. The trench bottom shows considerable gravel and a little gravel exists throughout the profile.	Fair	Practically level.	30
40	Sharkey clay	New Orleans, La.	0–8 dark brown or brown clay loam containing organic matter and full of grass roots. Rather compact. 8–30 stiff, plastic gray clay mottled with rusty colored material. No definite hard iron concretions. 30–60 gray silt loam mottled with rusty brown. The rusty colored spots get lighter in color with depth and practically disappeared at 60 inches.	Poor	Gently undulating to level.	30
41	Summit silt loam	Kansas City, Mo.	0–22 very uniform and smooth brown silt loam. 22–36 light brown smooth silt loam. 36–108 light brown uniform silt loam faintly mottled with grayish brown. Noncalcareous to 9 feet at which depth the soil is underlain by shale.	Fair	Gentle slope.	36
42	Susquehanna clay	Meridian, Miss.	Top soil corroded away. 0–6 rather compact but friable light reddish brown clay. 6–45 mottled red, yellow, and gray very hard compact clay that has a cubical structure. 45–56 mottled red, yellow and gray heavy silt loam. 56–84 same as 6–45.	Poor	Steep slope.	30

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
43	Tidal marsh	Elizabeth, N. J.	Entire soil profile, and especially the surface foot, contains a large percentage of undecayed organic matter and has a black color when wet. Upon drying the color changes to grayish brown. The soil contains hydrogen sulfide and a considerable amount of soluble salts, but no lime. The surface portion of the soil lost 20.7 percent on ignition.	Very poor	Level	36
44	Wabash silt loam	Omaha, Neb.	Except for the addition of grass roots to the top 8 to 12 inches, the entire profile consists of a uniform dark brown silt loam (black when wet) or silty clay loam, to a depth of at least 8 feet. Noncalcareous throughout.	Good	Practically level.	30
45	Unidentified alkali soil	Casper, Wyo.	0–6 light gray to light grayish brown sand to heavy silt loam. Little organic matter. 6–20 brown to grayish brown heavy, compact, gritty clay. Plastic and waxy when wet, but becomes hard and tough when dry. 20–30 abrupt change to a light gray sandy clay. More friable than upper horizon due to higher sand content. 30–48 sand content decreases, color slightly darker and texture more compact than above horizon. Type is highly alkaline, and white streaks and splotches of concentrated salts occur abundantly throughout the profile except in the surface soil.	Poor	Level	30
46	Unidentified sandy loam	Denver, Colo.	0–12 brown or light brown sandy loam. 12–14 layer of brickbats and debris. 14–20 light brown sandy loam. All the above material is loose and friable. 20–22 hard compact layer of cinders. All the above material is full and the next horizon is probably the original surface of the profile. 22–36 hard, compact brown sandy loam. 36–120 light brown sandy loam which gets a little lighter in color and is calcareous below 60 inches, where it is slightly cemented.	Good	Very gentle, uniform slope.	50
47	Unidentified silt loam	Salt Lake City, Utah	0–12 grayish brown or brown silt loam containing considerable organic matter. Highly calcareous at all depths. 12–72 light gray moderately compact clay containing occasional mottlings of brownish yellow and reddish brown. A few lime concretions and occasional water-worn pebbles that are partly coated with lime are present.	Poor	Moderate slope.	36

1	Acadia clay	Spindletop, Tex.	The area is a transition from Acadia clay to prairie of Lake Charles clay. The test site is in the two soil types. The 20 feet of south end of trench is Lake Charles clay. Acadia clay, prairie phase. 0–12 very dark gray (almost black) heavy acid clay spotted with yellowish brown. 12–30 dense gummy dark-acid clay with yellowish brown and rust brown spots and splotches. 30–60+ gray dense clay with yellow and yellowish brown spots. Large amount of fine soft crystals of gypsum, neutral in reaction. Lake Charles clay 0–24 black heavy clay 24–40+ yellow heavy clay with some gray mottling and fine crystals of gypsum.	Very poor	Level	30
52	Lake Charles clay loam (mound phase).	League City, Tex.	0–12 dark gray silt loam. White incrustation of soluble salts on the surface. 12–20 gray silty clay loam mottled with yellowish brown, containing some black concretions. 20–30+ gray and yellow dense gummy mottled clay containing a few calcium carbonate concretions. Parent material of calcareous clay lies several feet beneath the surface.	do	do	30
53	Cecil clay loam	Atlanta, Ga.	Same as site 3.			
54	Fairmount silt loam	Cincinnati, Ohio	0–5 gray or light yellowish gray gritty, friable, silt loam stained or specked with light gray and rust brown. Moderate quantity of small calcareous shale chips present. 5–12 light gray or light brownish gray gritty, slightly compact friable silt loam containing a large amount of small chips of calcareous shale and limestone. 12–24 gray calcareous thin beds of shale partly weathered to clay stained light gray. 24–34 dark gray bedded calcareous shale containing small irregular pockets of gray, plastic, heavy clay or partly weathered shale.	Poor	Steep slope	30
55	Hagerstown loam	Baltimore, Md.	Same as site 11.			
56	Lake Charles clay	El Vista, Tex.	0–12 black, noncalcareous, very heavy clay 12–32 dark bluish gray, noncalcareous, waxy clay 32–48+ light gray waxy, noncalcareous, clay with some yellow spots.	do	do	30
57	Merced clay adobe	Tranquillity, Calif.	Same as site 117.	do		
58	Muck	New Orleans, La.	Description not available Soil very similar to site 29	Very poor		
59	Carlisle muck	Kalamazoo, Mich.	0–13 black or vary dark gray granular, smooth, loamy, thoroughly decomposed organic material. Moderately acid. 13–30 dark gray fibrous, stringy, moderately compact plant remains partially decomposed and containing brown raw felty peat. Slightly acid. 30+ partly decomposed remains of swamp-loving plants displayed.	Poor	do	20

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
60	Rifle peat	Plymouth, Ohio	0–4 dark brown or brown loamy, smooth well-decomposed organic matter intermixed with finely fibrous, partly decayed vegetable matter that includes some woody material in different stages of decomposition. A small quantity of gray quartz grains is present throughout the layer. Strongly acid. 4–11 dark grayish brown, smooth loamy well-decomposed organic matter containing a large quantity of only partly decayed peaty material which includes fragments of partly rotted woody matter. Very strongly acid. 11–19 dark gray or brownish gray, loamy, smooth, well-decomposed, and finely divided partly decayed vegetation that includes some woody material in different degrees of decay. Very strongly acid. 19–26 very dark gray smooth, loamy decomposed vegetable matter interstratified with mottled layers of finely fibrous peaty material and thin seams of dark gray silt loam and clay mineral material. Very strongly acid. 26–34 bluish or bluish gray smooth, nongritty, tight, slowly pervious clay which displays mottles of light gray and stains of rust yellow with increasing depth. Medium acid. Specimens were buried in both the clay and peat layers	Very poor	steep slope	22
61	Sharkey clay	New Orleans, La.	Same as site 40.			
62	Susquehanna clay	Meridian, Miss.	Same as site 42.			
63	Tidal marsh	Charleston, S. C.	This soil is typical of the tidal marshes found along the seacoast. The soil materials from tidal marshes vary from dark, oozy sediments interspersed with coarse marsh-grass roots to a yellowish or dark colored clay. The subsoil and the free water in the soil are usually charged with hydrogen sulfide. A similar soil is site 43	do	do	
64	Docas clay	Cholame, Calif.	0–12 very dark grayish brown clay that is plastic when wet and has fairly large cracks when dry. Soil blocky and moderately compact when dry. Many salt crystals. 12–24 grayish brown clay that is plastic when wet and has friable consistance when moist. It has less visible lime than the surface soil but is highly calcareous. 24–30 similar to layer above, except that it contains many lime splotches. 30–42 light grayish brown clay mottled with gray	Very poor	Level	24–30

65	Chino silt loam	Wilmington, Calif.	This soil is a poorly drained phase of Chino silt loam. 0–13 dark-brown friable, micaceous, highly calcareous silt loam mottled with rust brown and gray silt loam or clay loam. 13–23 brownish gray highly mottled with rust specks, firm clay loam that is highly calcareous. 23–30 highly calcareous olive gray and grayish brown mottled, very fine sandy loam, not so much iron mottling as layer above. 30–48 highly calcareous gray silty clay loam, very plastic when wet and becomes light gray when dry.	....do.	Almost level.	36
66	Mohave fine gravelly loam. (Tucson fine gravelly loam).	Phoenix, Ariz.	This area is mapped as Mohave fine gravelly loam (highly calcareous phase), but it would now be classified as Tucson fine gravelly loam. Within the length of the trench is a thin stringer of Pinal fine gravelly loam. These two soils grade into each other and are therefore not typical of either. Descriptions of the two soil profiles follow. Mohave fine gravelly loam (Tucson fine gravelly loam). 0–1 fluffy white and pink alkali crust fine sandy loam, highly calcareous. 1–14 overwash material, reddish brown, highly calcareous, friable fine gravelly loam. 14–36 reddish brown, friable, highly calcareous gravelly loam with much gravel, lime coated. 36–48 soft caliche layer, reddish brown, much gravel. Pinal fine gravelly loam. 0–12 reddish brown, friable, highly calcareous fine gravelly loam with much loose gravel. More or less overwash material. 12–23 reddish brown loose, friable, highly calcareous gravelly loam. 23–36 hard caliche of lime carbonate, gravel and reddish brown fine sand loam.	Good	....do.	34–48
67	Cinders	Milwaukee, Wis.	Test site is adjacent to a canal and the trench is always more or less wet. The trench was evacuated to a depth of 5 feet and filled with fresh cinders, in which the specimens were buried to 3 feet. An analysis of the cinders showed it to contain 26 percent of carbon. Following is the description of the profile before backfilling with the cinders: 0–8 sandy clay with surface of a mixture of cinders, canal dust, and oxide. 8–17 layer of spent oxide purifying material containing iron borings and shavings with about 50-percent sulfur content and some cyanide compounds. 17–60 mixture of sandy clay and loam with appreciable quantities of marl and traces of cinders and ashes. 60+ stiff clay.	Very poor	Level	48

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
68	Gila clay	Phoenix, Ariz.	0–12 uniform chocolate brown granular, highly calcareous clay that is friable when moist. This layer is quite plastic when moist but not so much as the layers below. 12–24 uniform brown massive, firm, highly calcareous clay which gradually grades into. 24–36 more friable red tinted brown, highly calcareous clay that also grades into. 36–48 slightly mottled reddish brown, brown, and rusty brown, highly calcareous clay that is very plastic when wet. 48–60+ very little change in texture or lime content. Mottlings are more intense with depth.	Imperfect	Level	40
69	Houghton muck	Kalamazoo, Mich.	0–8 very dark gray or dark grayish brown smooth, loamy, thoroughly decomposed organic matter matted together with plant roots and intermingled with raw or partly disintegrated finely fibrous peaty matter. Contains some sand material. 8–24 dark gray smooth, slick, loamy well-decomposed vegetable matter containing finely divided partly decayed plant remains and brown raw fibrous peat. Layer thinly laminated and moderately compact and matted with fine roots penetrating through it. 24–35 brown raw, fine, fibrous peat containing dark or gray smooth, loamy partly decayed organic matter and mixed with a small, variable quantity of light gray sand material.	Poor	....do	24
70	Merced silt loam	Buttonwillow, Calif.	Same as soil 23.			
71	Mahoning silt loam	Austintown Junction, Ohio.	Description of profile not available. Soil type is subject to change upon better identification.			
72	Trumbull clay loam	Yale, Ohio	This soil is a dark bluish black when wet and has a pH of 7.2. When air-dried it is a light gray with a brownish cast and has a pH of 4.1. Active anaerobic sulfate-reducing bacteria have been identified here. Typical profile from soil survey report of Portage County. Surface—varies from a clay loam to a silty clay loam, generally of a somewhat bluish cast in very wet places. The drier portions have a brownish cast. The soil, while heavy, carries sufficient sand to be noticeable. Subsoil—consists of a clay loam to silty clay loam, light gray or gray mottled with some drab and brown. Clay content increases with depth and mottling usually becomes more pronounced. The gray generally changes to a bluish drab or even a steel-blue, soft, plastic clay. Presence of iron stains and concretions throughout the soil mass is characteristic.	Very poor	Gradual slope.	

73	Unidentified river bed	E. St. Louis, Mo.	Description of profile not available. Soil type is subject to change upon better identification.			
74	Otero clay loam	Rocky Ford, Colo.	....do			
75	Unidentified alkali soil	Albuquerque, N. M.	....do			
76	Chino silt loam	Los Angeles, Calif.	....do			
77	Susquehanna clay	Louisville, Miss.	....do			
78	Caddo fine sandy loam	Latex, La.	....do			
101	Billings silt loam (low alkali).	Grand Junction, Colo.	0–6 gray silt loam containing a few cinders and showing evidence of being disturbed. Rather compact and dry. 6–45 grayish brown slightly compact silt loam full of white streaks and spots. 45–108 grayish brown sandy loam, loose and rather wet at 108 inches.	Good	Very gentle uniform slope.	34
102	Billings silt loam (moderate alkali).	Grand Junction, Colo.	0–6 grayish brown silt loam, lighter than lower soil probably because it is dryer. 6–108 grayish brown silt loam mottled with white streaks and specks and containing a few thin layers of fine sandy loam below 36 inches.	Fair	Very gentle slope.	36
103	Billings silt loam (high alkali).	....do	0–2 surface crust underlain by mulch, grayish brown silt loam. 2–74 grayish brown heavy silt loam. White streaks and specks appear below 14 inches and become most numerous at about 6 feet. 74–108 light grayish brown micaceous fine sandy loam	....do		36
104	Cecil clay	Charlotte, N. C.	0–72 bright red clay, smooth and brittle with no noticeable change, except slight addition of organic matter in first few inches.	Good	Gentle slope	40
105	Cecil clay loam	Macon, Ga.	0–8 grayish brown sandy clay loam, pine needles and trash above 1 inch. 8–28 red brittle clay, compact and hard 28–72 micaceous light red silt loam 72–100 mottled red and yellow micaceous silt loam. No visible granite, but soil section has a few veins of quartz that have structure-like petrified wood.	....do	....do	26
106	....do	Salisbury, N. C.	0–4 grayish brown clay loam 4–72 red clay which gets a little more crumbly and slick with increasing depth.	....do	....do	36
107	Cecil fine sandy loam	Raleigh, N. C.	0–8 grayish brown fine sandy loam with a little gravel mixed with it, rather compact. 8–18 yellowish brown clay loam, more friable 18–34 red clay 34+ mottled, gritty red and yellow partially decomposed granite with some hard fragments of parent rock.	....do	....do	

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
108	Cecil gravelly loam	Atlanta, Ga.	0–2 grayish brown sand loam 2–42 typical red clay 42–72 red clay with mica crystals	Excellent	Gentle slope	36
109	Fresno fine sandy loam (low alkali).	Fresno, Calif.	0–2 loose grayish brown fine sandy loam 2–18 very hard, compact grayish brown, micaceous fine sandy loam containing a few light colored specks. Breaks with concodial fracture. 18–84 grayish brown compact shale-like micaceous very fine sandy loam containing rusty mottling in places. Light gray streaks between plates.	Poor	Level	36
110	Fresno fine sandy loam (moderate alkali).	....do	0–6 gray moderately compact fine sandy loam 6–18 compact light brown fine sandy loam 18–24 very hard, compact, tough layer, breaks with concodial fracture. 24–56 moderately compact light brown silt loam 56–68 light brown moderately compact fine sand 68–72 same as above with rusty mottling	....do	....do	
111	Fresno fine sandy loam (high alkali).	Kernell, Calif.	Description of profile not available. (See site numbers 109 and 110.)	....do		
112	Imperial clay (moderate alkali).	Niland, Calif.	0–50 brown shale-like compact clay with thin layers of a coarser material and gravel scattered through the profile. Practically no gravel on surface. 50–56 layer containing considerable gravel 56–72 brown clay	....do	Gentle uniform slope.	36
113	Imperial clay (high alkali)	....do	0–1 light brown crust 1–4 light brown mulch 4–96 brown clay with a slightly reddish or purplish cast, hard and compact with platy structure. If the entire profile had the same moisture content, it would probably have the same color. Texture is heavy throughout and practically no gravel or coarse material.	Fair	....do	36
114	Lake Charles clay	El Vista, Tex.	Same as soil 56.			
115	Memphis silt loam	Vicksburg, Miss.	0–12 grayish brown silt loam 12–72 light brown silt loam with slightly reddish cast. No lime or mottling.	Good	Gentle slope.	

116	Merced clay	Los Banos, Calif.	Description of profile not available. Profile most similar to site 117.	Fair		
117	Merced clay loam adobe	Tranquillity, Calif.	0–3 loose grayish brown mulch 3–18 dry, grayish brown clay, showing characteristic adobe cracks. The lumps are very hard, and the cracks are lined with light colored salts. Profile appears as though there was a heavy concentration of alkali at about 18 inches. 18+ moist clay with no well-defined structure	Poor	Level	24
118	Niland gravelly sand (low alkali).	Niland, Calif.	0–26 stratified light gray or grayish brown gravelly sandy loam 26–32 brown compact clay 32–54 light gray gravelly sandy loam—same as surface clay. 54–72 light grayish brown sandy clay	Fair	Moderate slope.	36
119	Norfolk sandy loam	Macon, Ga.	0–4 grayish brown sandy loam 4–50 yellowish brown or dirty yellow fine sandy loam. These two layers are rather compact. 50–84 pale red or reddish yellow open, loose clay loam 84+ gravel layer of variable thickness	Good		
120	Norfolk sand	Pensacola, Fla.	0–2 yellowish gray sandy loam 2–72 pale yellow fine sand with some clay mixed with it	....do	Level	40
121	....do	Tampa, Fla.	0–4 gray or grayish brown 4–12 gradually changes into pale yellow sand. Color typical of Norfolk at 12 inches. 12–66 yellow color increases in brightness and depth until it is a light brown with brownish yellow mottlings. Few iron concretions at 34 inches. Deeper subsoil has a little clay mixed with it.	....do	....do	36
122	Panoche clay loam	Mendota, Calif.	Typical profile from reconnaissance soil survey of the lower San Joaquin Valley, Calif. Panoche clay loam is a gray or brownish gray clay loam, rather low in organic matter content, and relatively high lime content. Subsoil occurs at a depth of 18–30 inches and resembles the surface in essential features. Calcareous, effervescing freely with sand, and the lime in many places is concentrated in seams, veins, and nodules. The deeper subsoil and substratum sometimes includes strata of small gravel, sand, and finer sediments.	Fair		
123	Susquehanna clay	Shreveport, La.	0–2 reddish brown fine loose sandy loam 2–14 red compact clay 14–42 compact mottled red to yellow clay 42–52 yellowish gray mottled with light gray clay 52–72 bluish gray compact clay	Poor	Steep slopes.	
124	Susquehanna silt loam	Troup, Tex.	Typical profile from soil survey of Rapids Parish, La. 0–4 brownish to grayish silt loam 4–12 pale yellow or mottled yellowish and grayish silt loam. 12+ yellow clay, which becomes mottled first with gray and in the lower part with red and drab. Lower subsoil is very plastic and adhesive when wet.	....do		

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
125	Susquehanna fine sandy loam.	Shreveport, La.	0–10 light-brown slightly compact fine sandy loam 10–30 yellowish-brown rather compact clay loam containing some sand, slightly mottled in lower part. 30–48 mottled red, yellow, and gray silt loam 48–72 mottled red, yellow, and drab clay. Compact and hard.	Poor	Moderate slope.	40
			AMERICAN PETROLEUM INSTITUTE SITES			
1	Bell clay	Temple, Tex.	Typical profile from soil survey report of Bell County, Tex. 0–12 black clay 12–30 gray, heavy plastic clay 30+ gray clay	Poor	Gentle slope.	
2	Oswego silt loam	Arkansas City, Kans.	Soil described as black, tough, heavy clay. Location of the site on the soil map accompanying the soil survey of Cowley County, Kans. shows the soil to be Oswego silt loam. The typical profile consists of a black silt loam, underlain at a depth of 6 to 10 inches by a clay hardpan consisting of black, tough, heavy clay. The material shows little change within the 3-foot section, except that in the lower part it is frequently lighter colored being very dark drab to very dark brown or nearly black with some yellowish brown and dark colored concretionary material. This type is the black equivalent of Gerald silt loam. It is locally known as "hardpan" land.	Good	Level.	
3	Lake Charles clay	Beaumont, Tex.	Same as National Bureau of Standards site 56.			
4	Lake Charles clay loam	League City, Tex.	This test site is in the same area as site 52 of the National Bureau of Standards sites. The National Bureau of Standards specimens were buried in the mound phase, which is different from the surrounding soil in which these specimens were buried. Typical profile from soil-survey report of Galveston County, Tex. 0–12 dark gray, very fine sandy clay loam 12+ gray clay	Very poor	....do	

5	Miami silt loam	Preble, Ind.	Typical profile from soil-survey report of Blackford County, Ind. 0–2 dark gray loose silt loam mixed with well-decomposed organic matter. 2–6 pale yellowish, gray friable silt loam that is soft and crumbly. The lower half contains very little organic matter. 6–12 heavier silt loam, which is rather firm but porous and has little or no definite structural arrangement. 12–24 moderately hard silty clay loam which breaks into aggregates from 1/8 inch to 1/4 inch in diameter. The granules separate easily when moist. Rust brown colorations in the lower part. 24+ dense and lighter-colored massive till, yellow stains occur along the fissures.	Poor	do
6	Unidentified	Council Hill, Okla.	Surface—dark brown friable clay loam Subsoil—yellowish brown clay	do	do
7	Oswego silt loam	Caney, Kans.	Soil type named from location on soil survey map of Montgomery County, Kans. Typical profile follows: 0–8 dark gray to black silt loam underlain abruptly 8–36 black or very dark brown heavy clay. Texture of the subsoil does not change with depth, but the color usually becomes slightly mottled with yellowish brown. 36+ yellowish brown color The soil at this test site has been identified as follows: Surface—black silt loam. Subsoil—heavy yellowish clay loam.	do	do
8	Acadia clay	Spindletop Gully, Tex.	Same as prairie phase at National Bureau of Standards site 51.		
9	Hanford fine sandy loam	Long Beach, Calif.	Soil type named from location on soil-survey map of the Anaheim Area, Calif. See National Bureau of Standards site 12 for typical profile.	Good	do
10	Muscatine silt loam	Mt. Auburn, Ill.	Typical profile from soil-survey report of Poweshiek County, Iowa. 0–2 very dark grayish brown or heavy black silt loam 2–18 very dark grayish brown silt loam that is very sticky when wet but friable when dry. In places the soil is heavy in texture, approaching a silty clay loam. 18–25 very dark brown silty clay loam 25–28 yellowish brown silty clay loam 28–42 yellowish brown silty clay loam mottled with gray. Conspicuous orange brown and rust brown iron stains and concretions. 42+ yellowish brown silty clay loam highly mottled with gray, with nodules, stains, or splotches of rust brown or black.	Poor	do
11	Unidentified	Skiatook, Okla.	Upper soil—striated brown sandy clay Subsoil—black clay Most of the line is in a salt wash.	do	do
12	Merced clay loam	Mendota (Tranquillity), Calif.	Same as National Bureau of Standards site 117.		
13	Miller clay	Bunkie, La.	Same as National Bureau of Standards site 27.		

TABLE 101.—*National Bureau of Standards test sites*—Continued.

Site No.	Soil type	Location	Description of soil profile	Internal drainage	Topography	Depth of specimens
						Inches
14	Hagerstown loam	Chambersburg, Pa.	0–6 loose, mellow dark brown silt loam 6–12 loose, yellowish brown silt loam 12–24 reddish yellow compact silty clay loam, becoming heavier with depth. Limestone was encountered at various depths from 24 inches to 36 inches.	Good	Gentle slope.	
16	Docas clay	Cholame, Calif.	Same as National Bureau of Standards site 64.			
			AMERICAN GAS ASSOCIATION SITES			
1	Cinders	Pittsburgh, Pa.	The soil is all fill (at least 10 years old) to a depth considerably below the bottom of the trench. It consists mostly of cinders from the gas plant, but also present was some boiler-flue dust, tar from retorts, clay, concrete, a little gravel, and other material. The dark colored and cleaner cinders were placed next to the specimens.	Good	Level	36
2	....do	Milwaukee, Wis.	Same as National Bureau of Standards site 67.			
3	Tidal marsh	Brockton, Mass.	This site is covered with about 6 inches of water at high tide. The soil consists of 12 inches of a thick mat of grass roots, which is underlain by gravel and sand mixed with organic matter. The lower part of the first foot is darker colored than the surface 6 inches, and it has a distinct odor of hydrogen sulfide.	Very poor	Level	12
4	....do	Atlantic City, N. J.	0–24 heavy mat of grass roots 24 + loose, semifluid mass	....do	Very gentle uniform slope.	18–24
5	Muck	West Palm Beach, Fla.	Muck is above sand, being about 3 feet deep at one end of the trench and a few inches deep at the other end. The sand was thrown out of the trench and muck placed next to the specimens to a depth of at least 1 foot all along the trench. Most of the muck is black, but it contains a few lenses of brown fibrous peat.	....do	Depression	24
6	....do	Miami, Fla.	0–8 black well-decomposed muck 8–16 transition layer 16–56 brown fibrous peat 56–72 black semifluid sand, which is white sand containing organic matter.	....do	Level	24

7	Cecil clay loam	Atlanta, Ga.	Same as National Bureau of Standards test site 3.			
8	....do	Raleigh, N. C.	0–4 grayish brown sandy loam 4–8 yellowish brown sandy loam of heavier texture than above horizon, which changes to red clay loam. 8–36+ red clay loam or clay merges into rotten rock characteristic of cecil soils.	Fair	Rolling	20
9	Susquehanna clay	Shreveport, La.	Same as National Bureau of Standards site 123.			
10	Miller clay	Shreveport, La.	0–72 dull red or reddish-brown clay containing occasional thin lenses of lighter textured material of the same color.	....do	Practically level.	24
11	....do	Bryan, Tex.	0–10 dark brown (almost black) heavy clay 10–72 mottled mixture of dull red and dark brown clay	Poor	....do	24
12	White alkali soil	Los Angles, Calif.	This soil is a Hanford fine sandy loam containing a large amount of sulfate. Otherwise the profile is similar to the National Bureau of Standards site 12.			
13	Black alkali soil	Los Angeles, Calif.	This soil is a Hanford fine sandy loam unusually high in carbonates. Otherwise the profile is similar to the National Bureau of Standards site 12.			
14	Marshall silt loam	Kansas City, Mo.	0–20 dark brown smooth silt loam 20–24 transition layer 24+ light brown silt loam	Excellent	Almost level	30

XVIII. APPENDIX 3. METHODS EMPLOYED IN CLEANING OF THE NATIONAL BUREAU OF STANDARD SOIL-CORROSION SPECIMENS

After the soil-corrosion specimens were removed from the trench the loose dirt was scraped off and the specimens were boxed and returned to the National Bureau of Standards. Precautions were taken in packing the specimens to prevent injury to the fragile materials during shipment. When the specimens arrived at the laboratory they were properly identified. The identification letter to identify the material and the number that associates the specimen with the soil to which it had been exposed were stamped on the specimens with steel dies. Each type of material was then subjected to an appropriate chemical and mechanical treatment to remove the corrosion products, with an insignificant loss in weight of uncorroded metal, and to prevent mechanical injury to the specimens.

1. CLEANING OF IRON AND STEEL SPECIMENS

The iron and steel specimens as they came from the field were lightly pounded with a small dull-pointed hammer to remove the lightly adhering corrosion products. If the specimens were in the form of pipes, the caps were removed and the inside of the pipes were washed in a cleaning fluid to remove the coating of grease that was applied prior to burial to prevent internal corrosion. The specimens, which were in the form of plates or sheet, usually had a bituminous coating applied to the two ends to protect the identification numbers. This coating was removed by means of an appropriate solvent.

Up to 1928, the iron and steel specimens were cleaned by pounding them with a small pointed hammer, then brushed with a stiff wire brush, and treated with a bath containing a solution of alkaline ammonium citrate heated to about 80° C. In 1928, air-driven tools were substituted for the hand-cleaning operations and were subsequently used on the iron and steel specimens, with the exception of the high-alloy steels.

The specimens were pounded with an air hammer employing tools of different shapes and sizes to remove the corrosion products and hard flakes of rust that adhered to the specimens. The specimens were next brushed with a stiff, circular wire brush attached to the shaft of a motor. Then the specimens were placed in an electrically heated enameled iron tank containing a 10-percent solution of ammonium citrate made alkaline by the addition of ammonium hydroxide. The bath was heated to about 80° C. The time the specimens were left in the bath varied, depending upon the amount of rust and the condition of the solution, a fresh solution cleaning them more quickly than a solution that had been used for some time. Usually, immersion in the bath for 2 to 8 hours was sufficient to clean most specimens. After removal from the bath, the specimens were scrubbed under running water with a stiff wire brush and dried with cotton cloths. Frequently, hard flakes of rust still remained on the specimens. These were pounded again with the air hammer and the process repeated until all the corrosion products were removed.

It was deemed advisable to make tests showing the effect of the various tools and of the citrate bath used on the loss of weight of the pipe. Unburied pieces of 3-inch steel pipe and 3-inch cast-iron pipes were used for these tests. The specimens were thoroughly cleaned by the process described. The air hammer was turned on full. For the actual cleaning of the specimens, however, the air is very seldom turned on more than one-third; and only about one-third as much pressure is applied to the hammer as was applied during this test.

The test procedure was as follows: The specimens were first carefully weighed. One-third of the outside area was hammered vigorously with a sharp-pointed tool; another third with a six-pointed semiblunt tool; and the final third was a sharp-edged tool. These three tools comprise all the tools used in cleaning the specimens. The specimens were then placed under the motor-driven wire brush, after which they were immersed in the citrate bath at 80° C for 8 hours. After removal from the bath, the specimens were scrubbed under running water with a wire brush, dried, and reweighed the following day. The results obtained from the tests are given in table 102.

The maximum total loss of metal due to the cleaning on the 3-inch specimens was 55 milligrams, and on the 6-inch specimens the maximum loss was 320 milligrams. If a corrosion loss of 100 grams is assumed on a specimen, the maximum loss would result in 0.06 of 1 percent for the 3-inch specimens, and 0.32 percent for the 6-inch specimens, an error which is unquestionably negligible for the steel and very slight for the cast-iron materials. In 1937 the greatest accuracy attainable on the balance for weighing 6-inch specimens was 100 milligrams. Also the hammering to which the test specimens were subjected was many times more severe than applied in the

regular cleaning process. The sharp-edged tool, which apparently was the cause of most of the loss due to the hammering, is very seldom used and then very carefully.

This method of cleaning was used for all the uncoated ferrous materials with the exception of the high-alloy-steel materials. These specimens usually did not require any further treatment after scrubbing them with a stiff wire brush under running water. Sometimes it was necessary to remove the corrosion products from the pits with a knife and to place the specimen in the alkaline citrate bath for 1 to 3 hours.

TABLE 102.—*Effect of mechanical cleaning of the specimens.*

Specimen	Original weight	Weight after using air hammer and wire brush	Weight after immersion in in bath and brushing	Total loss
	g	*g*	*g*	*g*
3-in. wrought iron	1660.450	1660.440	1660.415	0.035
3-in. open-hearth iron	1751.800	1751.785	1751.745	.055
3-in. Bessemer steel	1742.660	1742.650	1742.605	.055
....do	1765.875	1765.870	1765.830	.045
6-in. cast iron	6880.15	6880.09	6879.92	.23
....do	7053.40	7053.31	7053.11	.29
....do	6984.86	6984.70	6984.54	.32

2. CLEANING OF COPPER, COPPER-ALLOY, AND ALUMINUM SPECIMENS

The copper, copper alloys, and aluminum specimens as they came from the field were scrubbed with a wire brush under running water to remove the adhering soil. After the soil was removed, all of these specimens were cleaned by placing them in a solution of 5-percent nitric acid and 2½-percent oxalic acid for 5 minutes or less. After removal from the acid bath, the specimens were scrubbed with a wire brush under running water. If necessary, the treatment was repeated. One such treatment was usually enough to thoroughly clean all the specimens except those that had been exposed to Tidal Marsh. The specimens of brass, bronze, and copper from this soil were covered with a very adherent coating of black graphite-like material, which could not be removed or loosened by any reagent so far tried. The wire brush slightly scratches the softer metals but continued hard scrubbing with it on copper and aluminum did not produce a loss which could be observed.

Specimens which had already been cleaned were given the treatment described above. The results obtained are given in table 103. 5- and 10-percent solutions of sulfuric acid were also tried as cleaning solutions for the copper and copper-alloy specimens, but they did not clean as quickly or as well as the solution of nitric and oxalic acids.

TABLE 103.—*Effect of oxalic acid cleaning solution on nonferrous specimens.*

Material	Original weight	Loss of weight after—		
		5 minutes in bath	5 minutes more in bath	5 minutes more in bath
	g	*g*	*g*	*g*
Copper, H	92.17	0.03	0.00	0.00
Brass, B	86.34	.02	.02	.00
Bronze, L	428.04	.02	.02	.01
Aluminum, C1	26.68	.02	.01	.00
Al+1½ percent of Mn, C2	28.18	.01	.00	.01
Duralumin, C3	26.01	.01	.08	.08

3. CLEANING OF LEAD AND LEAD-COATED SPECIMENS

The lead-coated pipes and the lead sheaths removed from the test sites previous to 1937 were scrubbed under water with a fiber brush to remove the soil. They were then placed in a solution of 5-percent nitric and 2½-percent oxalic acids for about 5 minutes. After removal from the bath, the specimens were scrubbed under running water with fiber brushes and dried. If all the corrosion products were not removed, the treatment was repeated. Where the lead coating had failed on the pipe the rust flakes were chipped off with a pointed knife. Ammonium citrate solution cannot be used to remove this rust as the citrate attacks the lead.

Clean specimens of chemical and antimonial lead were given the above series of treatments, with the observed losses shown in table 104.

TABLE 104.—*Effect of nitric and oxalic acids on lead specimens.*

Material	Original weight	Loss of weight after—		
		5 minutes in bath	5 minutes more in bath	5 minutes more in bath
	g	*g*	*g*	*g*
Chemical lead, A	2131.87	0.18	0.14	0.02
Antimonial lead, H	2075.04	.11	.09	.05

After 1937 the lead specimens were cleaned by placing them in a water bath maintained at 80° to 90° C for several hours. The specimens were then scrubbed under running water with a fiber brush. The corrosion products were removed from the pits with a dull-pointed knife and again scrubbed under running water. Usually two or three such treatments were sufficient to clean the specimens.

4. CLEANING ZINC AND GALVANIZED SPECIMENS

Up to 1939 the best method that had been found for cleaning zinc and galvanized specimens was concentrated ammonium hydroxide. Dilute solutions of ammonia attacks the corrosion products less and the zinc more than the concentrated solutions. The specimens were scrubbed with a wire brush. Trials showed that a wire brush does not remove weighable amount of zinc even though the specimens were scrubbed harder than is necessary to clean them. The results reported in table 105 were obtained by placing specimens of clean zinc in concentrated ammonia for 5 minutes, which is sufficient time to remove the corrosion products off of most specimens.

TABLE 105.—*Effect of 10 percent ammonia solution on zinc specimens.*

Material	Original weight	Loss in weight after—		
		5 minutes in ammonia	5 minutes more in ammonia	5 minutes more in ammonia
	g	*g*	*g*	*g*
Standard zinc sheet, P	87.92	0.04	0.26	0.01
Zinc sheet, Z1	90.79	.07	.10	.05
Zinc plate, Z2	504.19	.06	.07	.03

The objections to working with an open bath of concentrated ammonium hydroxide resulted in the adoption of the following procedure for cleaning the zinc materials after 1939. The specimens were immersed in a 10- to 15-percent solution of ammonium chloride maintained at 75° to 85° C for 30 minutes. After removal from the bath, the specimens were scrubbed under running water with a wire brush. If any corrosion products remained on the specimens, the process was repeated. It was often necessary to loosen the flaky corrosion products by scratching the surface of the zinc with a dull knife.

Table 106 reports the loss in weight of two specimens of zinc plate.

TABLE 106.—*Loss of weight of zinc specimens caused by ammonium chloride bath and scrubbing.*

Material	Original weight	Loss in weight after—		
		30 minutes in bath at 75°C	Vigorous scrubbing with wire brush	30 minutes more in bath at 75°C
	g	*g*	*g*	*g*
Rolled zinc, Z	509.76	0.04	0.00	0.04
Die-casting zinc, CZ	504.00	.01	.01	.03

5. CLEANING OF CALORIZED PIPE

No satisfactory solution has been found for cleaning calorized pipe. Most of the corrosion products are rather loose and flaky. The specimens were cleaned by scraping and brushing the pipe.

6. CLEANING OF NONMETALLIC-COATED SPECIMENS

The nonmetallic-coated specimens were scrubbed under running water with a fiber brush until clean and then dried with cloths. After recording the condition of the coating one-half of the coating was removed from the specimens in order to observe the condition of the metal under the coating. The corrosion products were removed from the pits by means of a pointed knife.

XIX. APPENDIX 4. ACCUMULATION OF DATA, CALCULATIONS, AND METHODS OF REPORTING THE DATA

1. ACCUMULATION OF DATA

After cleaning the specimens, the loss of weight of each was determined and checked, with tolerances ranging from 1 milligram (0.000035 ounce) for light stainless-steel specimens to 0.1 gram for cast-iron specimens weighing in the neighborhood of 6 kilograms (13.2 pounds). These tolerances do not, of course, indicate the precision of the data, as corrosion losses were only small percentages of the total weights and ranged from less than a milligram to a few hundred grams. However, the factor that controls the accuracy of the data is the extent to which conditions in the field can be reproduced, and this factor varies within wide limits. Moreover, it is doubtful that this factor can be greatly improved without getting away from conditions to which pipe lines are subjected. Data on the corrosion of working pipe lines indicate that the results of corrosion can not be reproduced within very narrow limits.

After weighing the specimens, the deepest pits were measured and the measurements checked, usually with a tolerance of 0.004 inches. In measuring the pits of the first removals in 1924, the practice was to measure no pit that was less than 10 mils in depth and to measure at least the 5 deepest pits that were over 10 mils in depth. If the specimen did not have 5 pits greater than 10 mils in depth, the depth of the unmeasured pits was assumed to be 5 mils. This assumption was based on the fact that there were unmeasured pits ranging in depth between 0 and 10 mils. Thus, it is fair to assume an average depth of 5 mils.

For the removals made during 1926 and 1928 (second and third periods) pits were not measured when they were less than 20 mils in depth. Thus, on the assumption previously stated, an average depth of 10 mils was assumed as the value to use for each unmeasured pit.

For the fourth period (1930) and thereafter, no attempt was made to eliminate any measurements whatsoever. But pits greater than 6 mils in depth were measured wherever measurements could be obtained. When definite pitting occurred but there were no pits greater than 6 mils, the designation *P* was used. When metal attack occurred on the specimen but no definite pitting could be observed the designation *M* was used, and when the specimen was unaffected by corrosion, *U* was used.

Since 1930 it has been the practice to record the 6 deepest pits on all the pipe specimens and the 12 deepest pits on the sheet and plate specimens—6 pits from each side of the sheet or plate.

The depth gage (fig. 86, A) used at the National Bureau of Standards is an ordinary micrometer depth gage that can be read to the nearest 0.001 inch. The end of the shaft is pointed so as to reach the deepest part of the pit. The base is cut away near the shaft so that the position of the point can be seen, and the originally flat base is machined to a concave cylindrical surface of ¾-inch radius. the long axis of the base being parallel to the axis of the cylinder. The gage then will not rock when placed on a 1½-inch or larger pipe surface with the long axis of the base parallel to the pipe axis. The length of the base has also been increased by a bridge for making measurements on severely corroded specimens.

The zero setting of the gage must be corrected for the curvature of the pipe surface. This was done by placing the gage on a smooth curved cylinder having the same diameter as the specimen and adjusting the micrometer to read zero. For measuring the pit depths of sheets or plates, the zero reading of the micrometer was adjusted by setting it on a smooth, polished, level surface. Ewing [29] has worked out a formula for setting the micrometer on a plane surface and adjusting the gage for the diameter of the pipe to be measured.

During recent years a different type of micrometer (fig. 86, B) has been used for making the pit-depth measurements, which appears to be less tiresome on the eyes

of the observer. The principle of this micrometer is the same as the previously mentioned gage, and the readings can be made to the nearest 0.001 inch on a dial. The base of this gage was machined to a narrow edge, so corrections for the curvature of the pipe were not necessary. A needle extending from the base was moved about in the pit until a maximum reading was obtained on the dial. The zero setting of the gage was adjusted on a smooth, polished, level surface. Check measurements with the two gages gave results that were within the tolerances allowed for the check measurements.

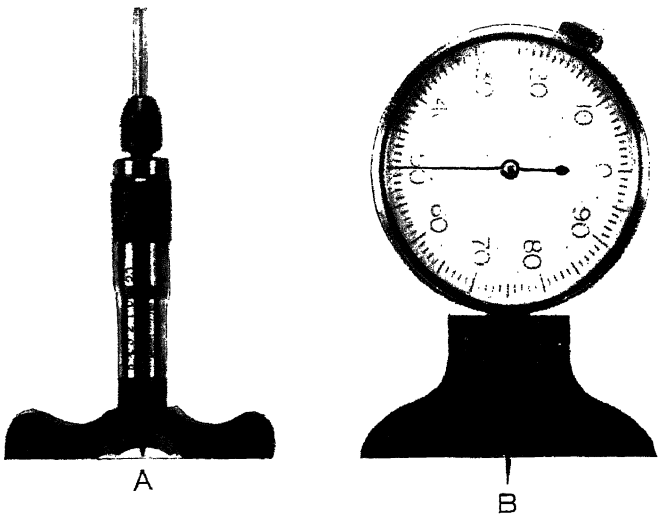

FIGURE 86.—*Pit-depth gages.*
A, Micrometer gage; *B*, dial gage. Each reads in thousandth of an inch-mils.

Having accumulated the loss of weight and pit-depth data, the specimens were next labeled and photographed. The pipe specimens were photographed by a circuit camera employing panoramic film (6-inches in width) while the pipes were rotating. In this manner photographs of the specimens 6-inches long were obtained in their actual size. For specimens longer than 6-inches the part showing the severest corrosion was photographed. Pictures were made of all the specimens on which appreciable pitting could be detected. The specimens were then given a coat of colorless varnish to prevent further rusting, and the specimens were preserved at the National Bureau of Standards until 1942, when the demand was made for all available scrap metal for the war effort. All the specimens except the last removals from each set were then turned over to the scrap drive.

2. CALCULATIONS AND METHODS OF REPORTING THE DATA

Usually two specimens of each material were removed from each test site. Hence, the data for losses of weight, rates of loss of weight, maximum penetration, and rates of maximum penetration for the tables involving the National Bureau of Standards tests in section V and to the numerous progress reports referred from the Journal of Research of the National Bureau of Standards are the arithmetical averages of two measurements. When one specimen was missing the value given is the actual value for the loss of weight or maximum penetration of the remaining specimen.

The weighings were always made employing the metric system. Hence, the losses in weight were obtained in grams. For the purpose of comparison, the losses were reduced to ounces per square foot since many of the specimens differed in exposed area. To do this, the loss of weight in grams was multiplied by a factor which gave the loss of weight in ounces per square foot directly. This factor was calculated for each material by the equation

$$\text{Factor} = \frac{1}{\text{ft}^2 \text{ of exposed area} \times \text{g/oz}} = \frac{1}{28.35A},$$

in which A is the area in square feet. To obtain the rate of loss of weight in ounces per square foot per year the loss in ounces per square foot was divided by the time of burial in years.

The data have often been reported as the average total penetration, which is derived from the loss of weight, the area exposed, and the density of the material. To calculate the average total penetration (in mils) the loss of weight (in ounces per square foot) was multiplied by a factor obtained as follows:

$$\text{Factor} \quad \frac{12 \times 1000}{\text{wt of ft}^3 \text{ of metal (lb)} \times 16} = \frac{750}{\text{density (lb/ft}^3)}.$$

The ratio of the maximum penetration to the average total penetration is the pitting factor. The pitting factor is to some extent a function of the area of pipe surface considered and usually has been found to be somewhat smaller for the 1½-inch specimens than for the 3-inch specimens of similar material.

The method for obtaining the maximum penetration has already been described. The rate of maximum penetration (in mils per year) is the ratio of the maximum penetration to the time of burial in years. For the purpose of comparing pit depths on pipes of different sizes, the data were reported as the weighted maximum penetration for each material. The exposed area of one 6-inch specimen is equivalent to the exposed area of two 3-inch specimens, and likewise the exposed area of one 3-inch specimen is equivalent to the exposed area of two 1½-inch specimens. Therefore, as there are two specimens for every material, the weighted maximum penetration was obtained as follows: For the 1½-inch specimens the value represents the arithmetical average of the deepest pit on each specimen, a total of two pits for each material. For the 3-inch specimens it represents the arithmetical average of the two maximum pits on each specimen, a total of four pits for each material. For the 6-inch specimens it represents the arithmetical average of the four maximum pits on each specimen, a total of four pits for each of the L and Z materials, as only one specimen of each were taken up at each removal and a total of eight pits for the other 6-inch specimens. The weighted maximum rate of penetration was obtained by dividing the weighted maximum penetration by the time of burial in years.

XX. APPENDIX 5. CONSTRUCTION OF THE DENISON CORROSION CELL

The dimensions and construction of Denison's most recent modification of his corrosion cell, which differ somewhat from those described in earlier papers, are shown in figure 87. The essential parts of the cell are a bakelite ring 44 mm (1.73 in.) in internal diameter and 21 mm (0.83 in.) high, a metal disk 38 mm (1.50 in.) in diameter, which serves as the anode, another disk of the same material 44 mm (1.73 in.) in diameter, which serves as the cathode and is perforated with 51 holes per square centimeter (329 per square inch), the diameter of each hole being 0.84 mm (0.033 in.). The metal disks are cut with a punch and die from sheet material. A narrow tab, or projection, is provided on the cathode to facilitate electric connection. The total area of the perforated disk is approximately twice the area of one side of the anode.

The other constituents necessary for construction of the cell are the soil samples to be studied which are air-dried and crushed to pass a No. 20 U. S. Standard Sieve, a nonmetallic disk 51 mm (2.00 in.) in diameter containing many perforations and having a hole in the center large enough to permit a calomel electrode to make contact with the adjacent soil, a No. 7 rubber stopper, rubber bands, and a short length of No. 24 copper wire.

The procedure in setting up the cells is as follows. The perforated cathode is cemented in place on a shoulder in the Bakelite ring so that the shoulder becomes a part of the compartment having a height of 10 mm (see fig. 87). This compartment will hereafter be referred to as the shallower compartment or as the lower part of the cell. To fit the cathode in the ring, it is necessary to cut a slit adjacent to the shoulder to allow the projection to pass through. The free space in the slit is sealed with plastic wood. The disk is then cleaned with carbon tetrachloride, using a small stiff fiber brush. The cells in sets[7] of 10 are filled with the soil samples. The shallower compartment is filled first by temporarily placing a disk of filter paper on the reverse side of the cathode to keep the soil from running through the perforations. The cell is then placed on the end of a cylinder about 4 cm high and 4 cm in diameter. The crushed soil is placed in the compartment in increments and packed by placing on the surface of the soil a brass cylinder weighing 500 grams and having a diameter of 44 mm. A disk of filter paper is placed on the soil and moistened with water from a burette. The cell is now inverted, placed on a smooth

[7] The laboratory setup at the National Bureau of Standards was made to accommodate 10 cells. However, a setup may be prepared for a different number of cells.

piece of glass, the filter paper removed, and the lower compartment filled and packed as before. The soil is then saturated by allowing it to absorb water from a strip of filter paper, the cell being supported by 2.5 cm above the surface of the water into which the filter paper dips. The period required for saturation is about 2 hours for most soils. Each cell is placed in an individual dish and covered by a beaker to prevent evaporation. Smoothing of the surface should be avoided after the soil has been moistened.

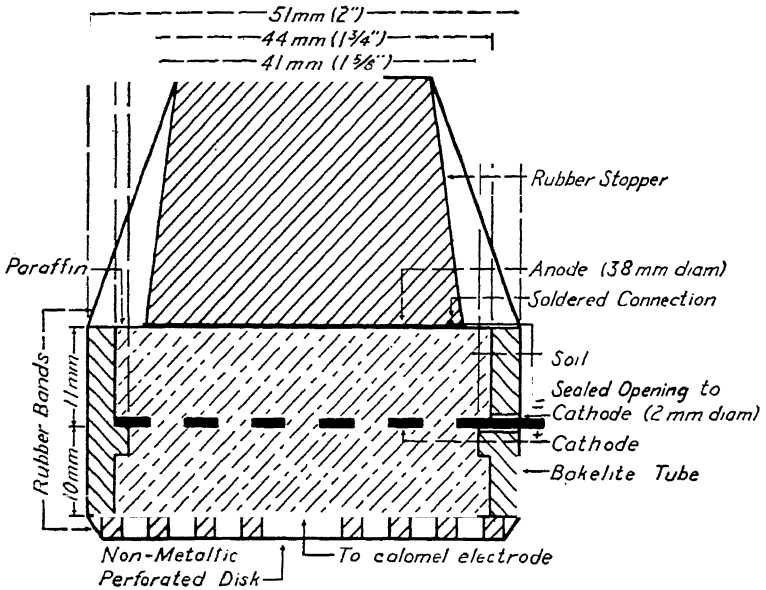

FIGURE 87.—*Denison corrosion cell.*

The moistening of very heavy soils may be accelerated by adding a slight amount of water to the upper surface of the soil. A sheet of filter paper on the surface of the soil facilitates even distribution of the moisture. The soils are brought under moisture equivalent (the quantity of water retained by a soil under a centrifugal force of 1,000 times gravity) by the method of Schofield [206], as described below.

A battery of ten 3-inch (7.6 cm) Buchner funnels set in pressure flasks is prepared by pouring on a filter paper placed in each funnel a sufficient quantity of a thin suspension of kaolin in water to produce under suction a layer about 1 mm thick. This layer permits any desired pressure difference up to 1 atmosphere between the interior of the flask and the outer surface of the layer to be maintained. A second piece of filter paper is placed over the kaolin layer and saturated with water, after which the cells are placed in position top down on the paper. A pressure difference of 10 cm of mercury is held for 1 hour, after which it is increased in increments of 5 cm every 10 minutes until a pressure difference of 59 cm is reached. The latter pressure maintained for 1 hour reduces the moisture content of a saturated soil to moisture equivalent. In testing organic soils such as peats, mucks, and tidal marsh, in which the average moisture content in nature is often close to saturation, it is preferable to reduce the moisture content only slightly below saturation rather than to moisture equivalent. This may be accomplished by subjecting the cell to a pressure difference of 5 cm of water for one-half hour.

During the adjustment of the moisture content, the anodes are prepared by rubbing one face with No. 1G French emery paper. After cleaning the electrodes with carbon tetrachloride, a No. 24 copper wire is soldered to the reverse side of the anode near the edge.

After the soils have reached proper moisture content, the pressure is released and the cells are removed from the funnels. Because shrinkage of the soil results from the withdrawal of water, a crack will often be noticed between the soil and the rim of the Bakelite cylinder. As a crack would provide a channel through which air could pass to the electrodes, it is necessary to seal it with melted paraffin, which is applied by means of a medicine dropper. The anode is placed in position over the

top of the cells and electric connection is made between anode and cathode by joining the copper wire with the projection on the cathode. The perforated insulating disk is placed over the lower end of the cylinder. A No. 7 rubber stopper is then placed on the anode and the whole assembly fastened together by rubber bands. It is especially important that firm contact be maintained between the electrodes and the soil.

The cells are placed in individual 1-pint friction-top cans into which a small amount of water has been poured in order to maintain a saturated atmosphere. In order to prevent a water seal, which would interfere with proper aeration of the cathode when the cell is placed in the can, the cell is inserted in a small glass dish about 4 cm in height and slightly larger than the cell in diameter. The rubber bands around the cell support the cell in the dish in such a way that free circulation of air is insured. A small amount of water is poured into this dish also. After the lids have been sealed, the cans are placed in a thermostatically controlled constant-temperature chamber and maintained at 25° C for 18 to 36 hours in order to stabilize the electrodes. If the room temperature is fairly constant at approximately 25°C, this last step may be omitted. The cells are removed from the cans when the electrical measurements are made, precautions being taken to prevent evaporation of moisture.

XXI. APPENDIX 6. DARNIELLE'S MODIFICATION OF THE HICKLING APPARATUS FOR MEASURING POTENTIALS

The Hickling method for measuring the potential of polarized electrodes utilizes an electronic interrupter and an electronic potentiometer, by means of which potentials can be measured a very short time after the current has been interrupted.

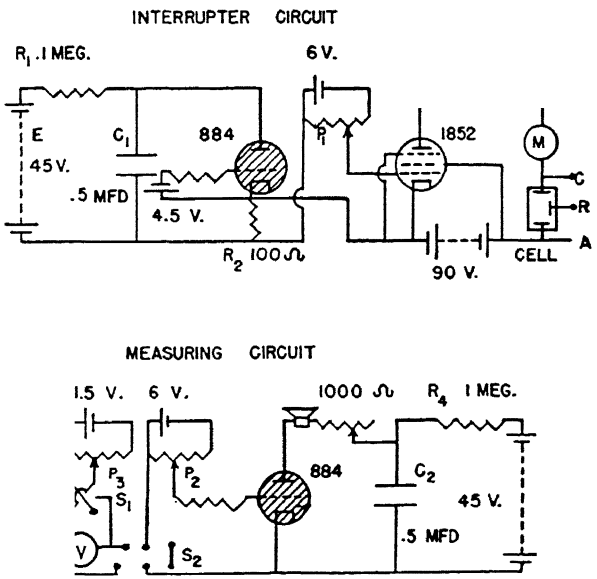

FIGURE 88.—*Potentiometer-volt meter and calibration circuit.*

Figure 88 shows the essential parts of the interrupter and measuring circuit. Capacitor C_1 is charged through resistor R_1 until the plate of the Thyratron (type 884) is at a certain potential, depending on the grid voltage. The tube then becomes conducting and capacitor C_1 discharges through the tube and resistor R_2 until the capacitor voltage drops to about 15 volts, when the tube becomes nonconducting, and the process is repeated at a rate depending on the values of E_1, R_1, C_1, and E_2.

The cell is in the plate circuit of the pentode (type 1852). Its current may be controlled by potentiometer P_1 and the IR drop across R_2. Each voltage pulse across R_2 imparts a large negative potential to the grid of the vacuum tube, thereby interrupting the current in the cell. Resistors should be connected in series with the grid of each Thyratron to limit grid current when the tubes conduct current.

The measuring circuit is an oscillating type similar to the interrupter circuit but will not oscillate when the grid of the Thyratron is below a certain critical potential.

In measuring electrode potentials, the electrodes are connected to the grid circuit of a Thyratron, the grid having been adjusted to the critical potential. The cell is so connected that the grid of the Thyratron is most negative between interruptions of the current because of IR drop in the cell. When the current is interrupted, the grid potential will be above or below the critical potential by an amount equal to the potential of the electrode. Adjustment of a potentiometer in the grid circuit, so that the critical potential is restored, measures the electrode potential.

In operation, double-pole double-throw switch S_2 is closed to the right (fig. 88), and the grid of the Thyratron in the measuring circuit is adjusted to the critical point by means of potentiometer P_2, as indicated by slow ticking in the loud-speaker. By reversing switch S_2, the cell and the voltmeter-potentiometer are introduced into the grid circuit of the Thyratron. If the applied voltage makes the grid more negative than the critical voltage, no sound will be heard in the loud-speaker. If the grid is made more positive than the critical voltage, very rapid ticking will be heard. Potentiometer P_3 is then adjusted until the rate of ticking is identical with the rate when the critical point was adjusted, and the potential difference is read on the voltmeter.

It is important to note that the connections of the measuring circuit to the cell are determined by the directions of IR drop and not by the polarity of the electrodes. Hence in measuring the voltage between the anode and cathode of the cell, the cathode of the cell is connected to the grid. When the voltage between the anode and a reference electrode is measured, the reference electrode is connected to the grid, and for measuring the voltage between the cathode and the reference electrode, the cathode of the cell is connected to the grid. A switching arrangement, not shown in detail in the figure, is used for making rapid changes in connecting to the various electrodes.

When the cell current is interrupted, it drops quickly to a very low value and immediately begins to increase as C_1 discharges. The time required for the current to decrease to a minimum and then increase until the IR drop is more than 0.01 volt, the approximate limit of accuracy of the measurement, may be designated as the "effective" period of interruption. This interval corresponds to the maximum time during which the electrode depolarizes before its potential is measured.

Hickling's measurements were made with high current densities in cells of very low resistance, a triode being used as the vacuum tube. In order to make the effective period of interruption independent of the polarizing current, the latter was controlled by adjusting the filament current. For measuring potentials in soil cells in which the resistance is high and the current low, the use of a sharp cutoff pentode permitted control of the plate current in the usual way, that is, by regulation of the grid voltage. By eliminating lag in the adjustment of the current in this manner, potential measurements could be made immediately after the current was changed, which is usually desirable in measurements with soil cells. With variation of current and resistance over the extreme range used in corrosion studies, the effective time of interruption was found to be reasonably constant. However, the chief advantage of the pentode over the triode was the greatly improved accuracy of measurement obtained with the former tube. Pentodes of the types 6J7 and 1852 have a very sharp cutoff and provide sufficient plate current for potential measurements in the soil cells. Calculation of the effective period of interruption indicated that this time was about 8×10^{-5} second when R_2 was 75 ohms.

Data show that within the range of current commonly applied to soil-corrosion cells and within the normal range of resistance of these cells, the combined effect of current and resistance on the accuracy of potential measurements is not over 0.01 volt. Measurements accurate to 0.01 volt were made with a current of 4 milliamperes and a cell resistance of 6,000 ohms.

As the period of interruption of the current is related to the resistance R_2 in the interrupter circuit, varying this resistance provides a convenient means for varying the period of interruption, and hence for studying the rate of depolarization of the soil cells. This was found to be subject to wide variation. In a few soils the change in voltage resulting from a change in R_2 from 100 to 20,000 ohms was little more than 0.01 volt. In other soils this difference was 0.1 volt or more. Rapid depolarization may occur at the anode as well as at the cathode. This period of interruption of the current should be kept as short as possible by keeping R_2 at the lowest practicable value. Measurements of cell potentials by means of the apparatus described have been found to be in good agreement with those by other less generally applicable methods.

WASHINGTON, June 19, 1945.

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